

Single-Spin Asymmetries at HERMES

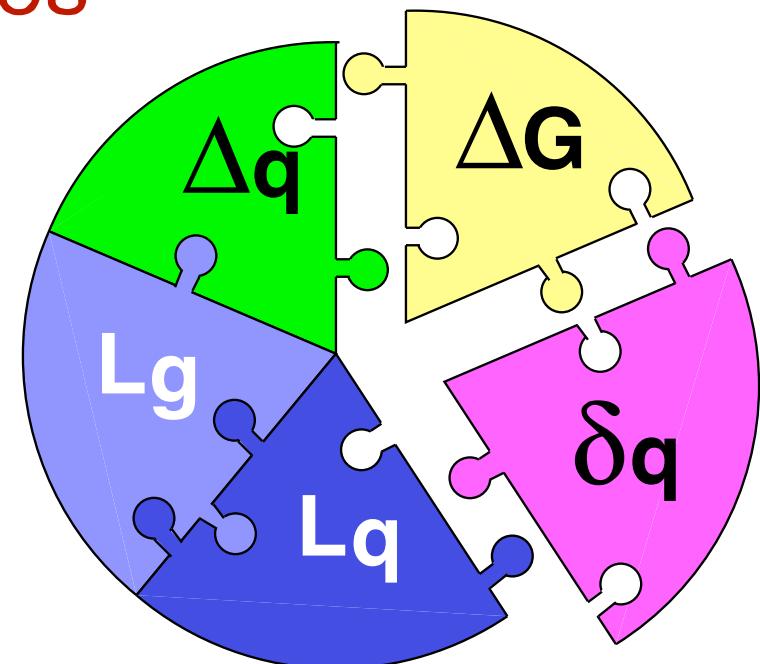
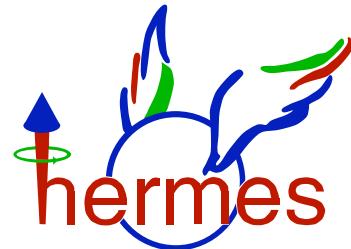
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SSA Workshop, BNL, Jun 1–3, 2005

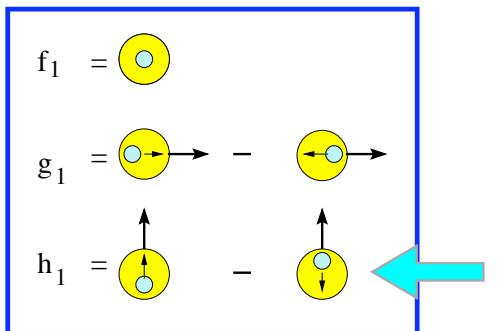
Outline

- *Introduction: SSA's & T-oddness*
- *First A_{UT} results from 2004 data*
- *Ongoing interpretation of Collins & Sivers*
- *Revisiting A_{UL} : twist-3 isolation*
- *First IFF results from Run 2*

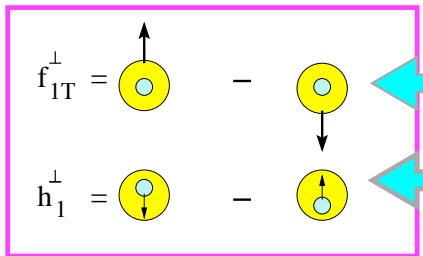


Functions surviving on integration over Transverse Momentum

Distribution Functions



transversity



Sivers

Sokolov-Ternov?

$$h_{1L}^\perp = \text{yellow circle with arrow} - \text{yellow circle with arrow}$$

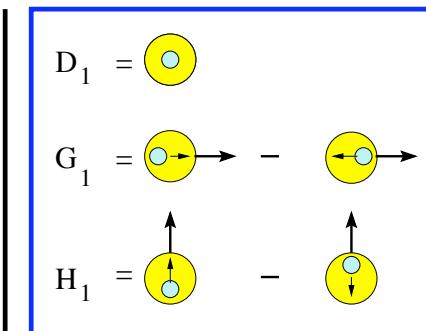
$$h_{1T}^\perp = \text{yellow circle with arrow} - \text{yellow circle with arrow}$$

Functions Odd under naive Time Reversal

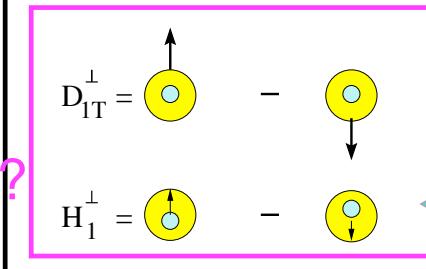
The others are sensitive to *intrinsic k_T* in the nucleon & in the fragmentation process

Mulders & Tangerman, NPB 461 (1996) 197

Fragmentation Functions



$$G_{1T} = \text{yellow circle with arrow} - \text{yellow circle with arrow}$$



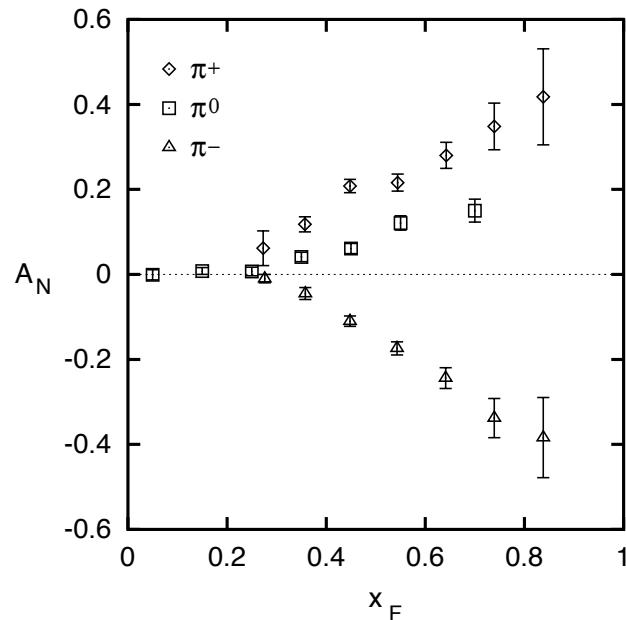
$$H_{1T}^\perp = \text{yellow circle with arrow} - \text{yellow circle with arrow}$$

Collins

One T-odd function required to produce *single-spin asymmetries* in SIDIS

Single-Spin Asymmetries at Hard Scales

E704: $p^\uparrow p \rightarrow \pi X$



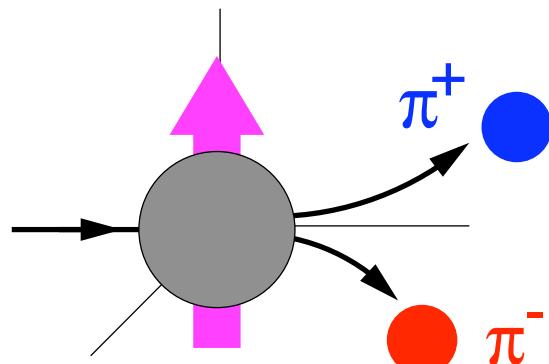
T-odd observables

SSA observables $\sim \vec{J} \cdot (\vec{p}_1 \times \vec{p}_2)$
⇒ **odd** under naive **time-reversal**

Since QCD amplitudes are T-even, must arise from **interference** between **spin-flip** and non-flip amplitudes with **different phases**

Suppressed in pQCD hard-scattering

- q helicity flip suppressed by m_q/\sqrt{s}
- need α_s -suppressed loop-diagram to generate necessary phase



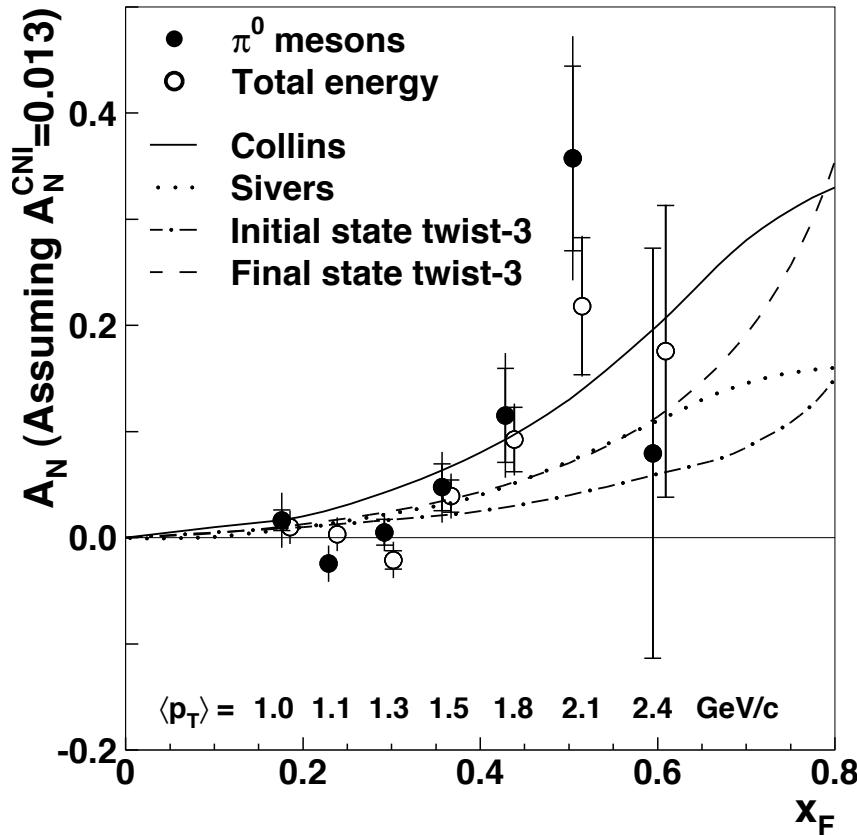
At hard (enough) scales, SSA's must arise from soft physics: T-odd distribution / fragmentation functions

Results from STAR: $A_N^{\pi^0}$ at forward rapidity

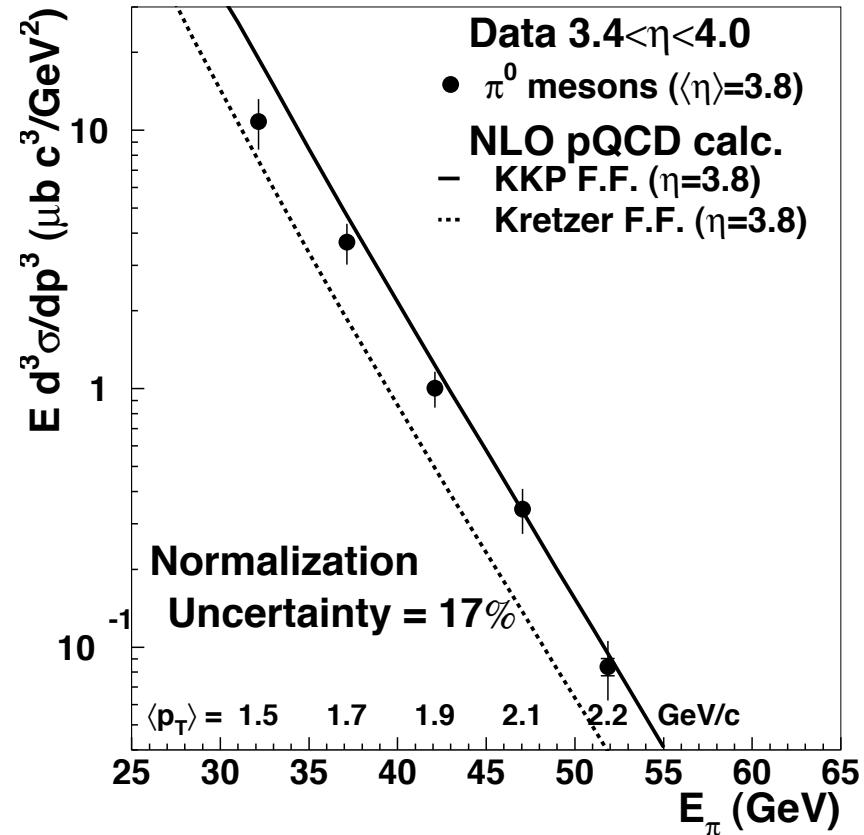


Was E704 at a hard-enough scale for reliable pQCD analysis?
well RHIC certainly is!

clear evidence of analyzing power



xsec well-described by pQCD



asymmetry shows similar **rise with x_F** as observed at E704

Possible Mechanism #1: The “Collins Effect”

Need an ordinary distribution function ... **transversity**

$$q(x)$$

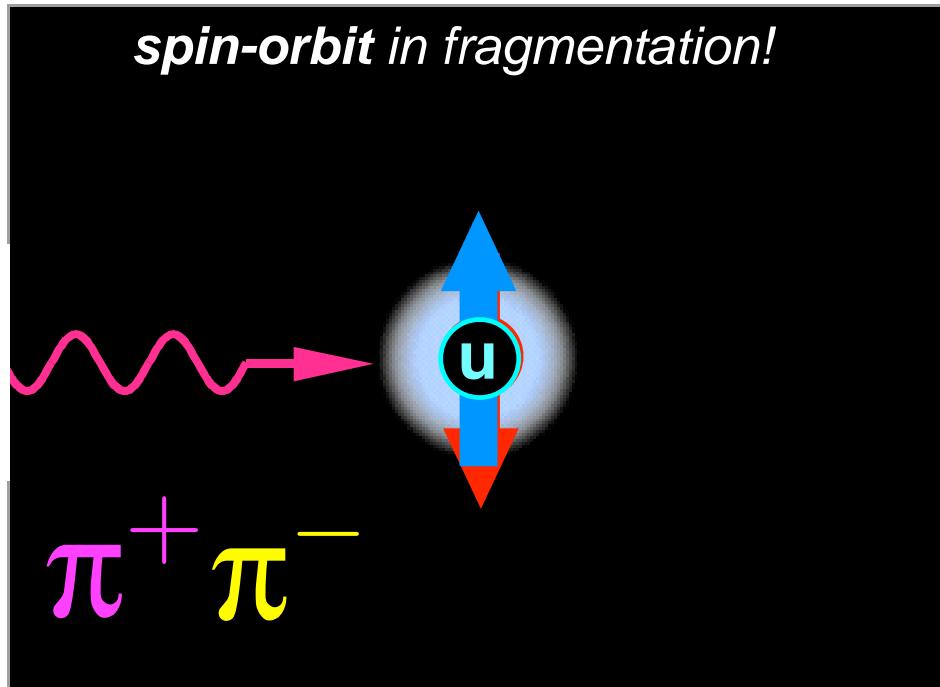
$$\Delta q(x)$$

$$h_1(x)$$

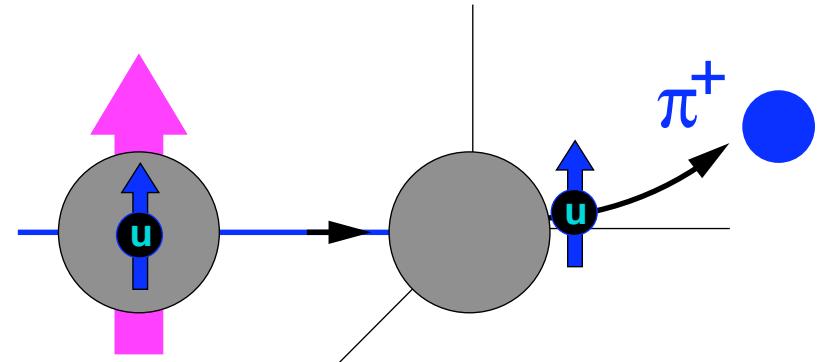
... with a new, **T-odd “Collins” fragmentation function**

$$H_1^\perp(z, p_T)$$

spin-orbit in fragmentation!



E704 effect:



$$h_1(x) \otimes H_1^\perp(z, p_T)$$

Possible Mechanism #2: The “Sivers Effect”

Need the ordinary fragmentation function

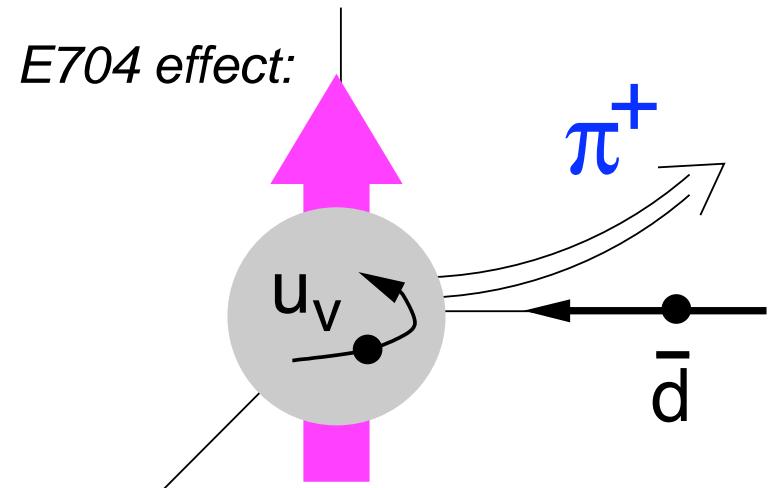
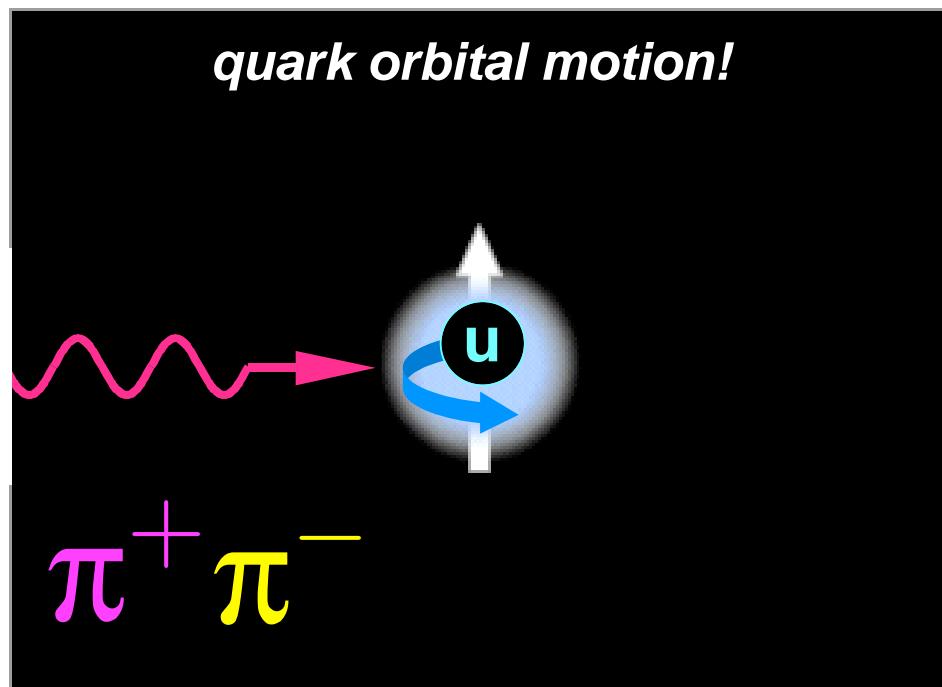
$$D_1(z)$$

... with a new, T-odd “Sivers” distribution function

$$f_{1T}^\perp(x, k_T)$$

Phenomenological model of **Meng & Chou**:

Forward π^+ produced from **orbiting valence-u quark** by
recombination at front surface of beam protons

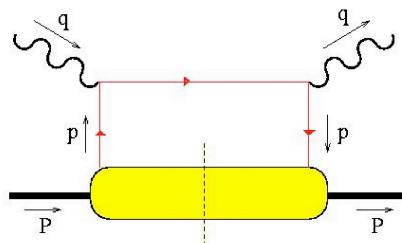


The Leading-Twist Sivers Function: Can it Exist in DIS?

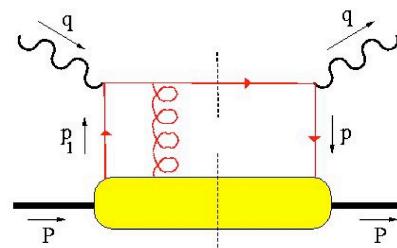
A T-odd function like f_{1T}^\perp must arise from **interference** ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?

$$\left| \text{Diagram} \right|^2 \sim \text{Im} \left\{ \text{Diagram} \right\}$$

Brodsky, Hwang, & Schmidt 2002



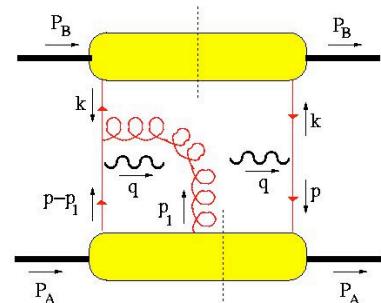
can interfere
with



and produce
a T-odd effect!
(also need $L_z \neq 0$)

*It looks like higher-twist ... but no, these are soft gluons
= “gauge links” required for color gauge invariance*

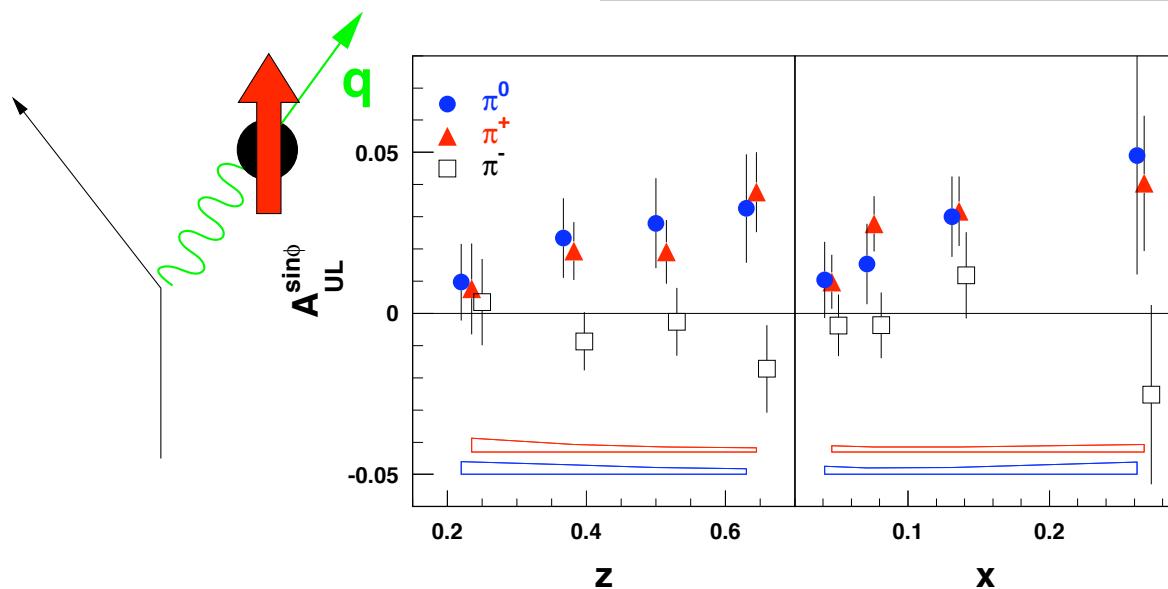
Such soft-gluon reinteractions with the soft wavefunction are final (or initial) state interactions ... and may be process dependent! → new universality issues



e.g. Drell-Yan

Results from Run 1 ...

$A_{\text{UL}}^{\sin\phi}$ Behaviour



Original Predictions of Collins

Collins, NP B396 (1993) 161

- Effect should peak at $x \simeq 0.3$ (valence)
- Effect should be stronger for π^+ than π^- (u -quark dominance)
- Effect should grow with p_T and peak at $p_T \simeq 1 \text{ GeV}/c$

$$A_p^{\pi^+} \approx \frac{4\delta u + \eta\delta d}{4u + \eta d} \approx \frac{\delta u}{u}$$

$$A_p^{\pi^0} \approx \frac{4\delta u + \delta d}{4u + d} \approx \frac{\delta u}{u} - \Delta$$

$$A_p^{\pi^-} \approx \frac{4\eta\delta u + \delta d}{4\eta u + d} \approx 0$$



We all thought DIS was Collins-only, so

$$A_{\text{UL}}^{\sin\phi} \approx \frac{\sum_q e_q^2 h_1^q H_1^{\perp q \rightarrow h}}{\sum_q e_q^2 f_1^q D_1^{q \rightarrow h}}$$

(sort of, modulo twist-3 effects ...)

Similarity between π^+ and π^0

... guess $\delta u > 0$ and $\delta d \approx -\delta u/2$...

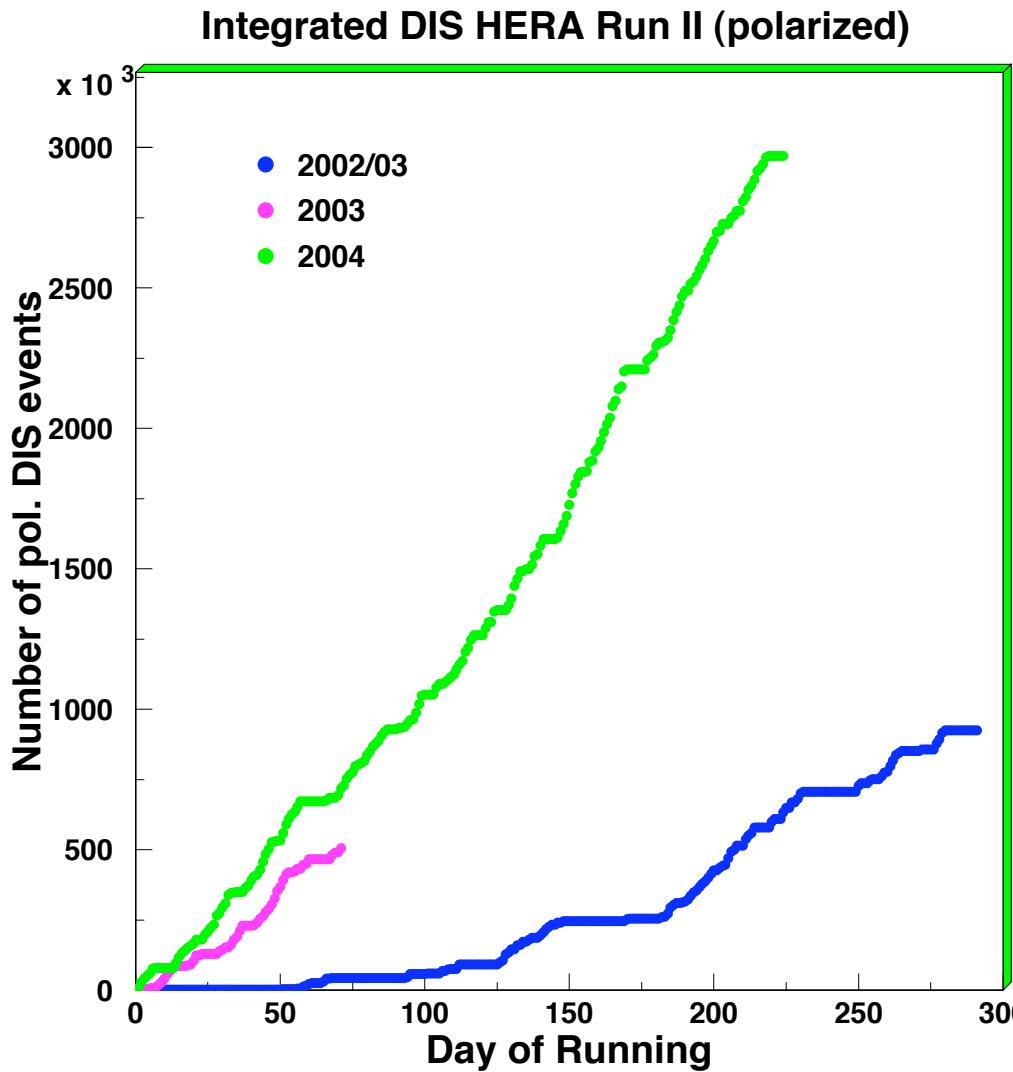
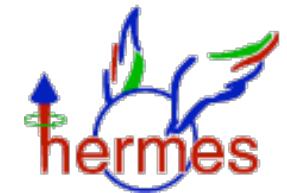
Favoured frag. func. $D_{\text{fav}} = D_u^{\pi^+} = D_d^{\pi^-}$

Disfavoured frag. func. $D_{\text{dis}} = D_d^{\pi^+} = D_u^{\pi^-}$

$$\rightarrow \eta \equiv \frac{D_{\text{dis}}}{D_{\text{fav}}} \approx \frac{1-z}{1+z} \approx \frac{1}{3}$$

Data Collection 2002 - 2004 and Cuts

Transverse Hydrogen target installed in 2001

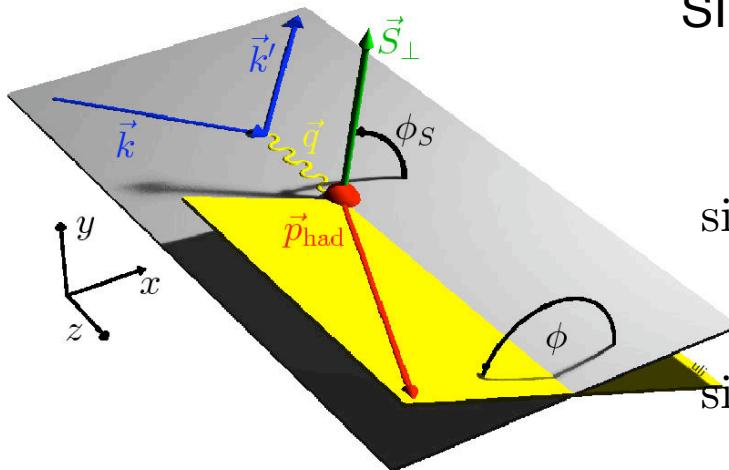


SIDIS cuts

- $0.1 < y < 0.85$
- $0.023 < x < 0.4$
- $Q^2 > 1 \text{ GeV}^2$
- $W^2 > 10 \text{ GeV}^2$
- $0.2 < z < 0.7$
(avoid exclusive region)
- $20 \text{ mrad} < \theta_{\gamma\pi}$

| year | target | spin | # DIS |
|--------------|----------|----------|----------------|
| 96–97 | H | L | 2.4 M |
| 98–00 | D | L | 9.3 M ☺ |
| 02/03 | H | T | 0.7 M ☹ |
| 03–04 | H | T | 2.8 M ☺ |

T-odd Distribution vs Fragmentation Function

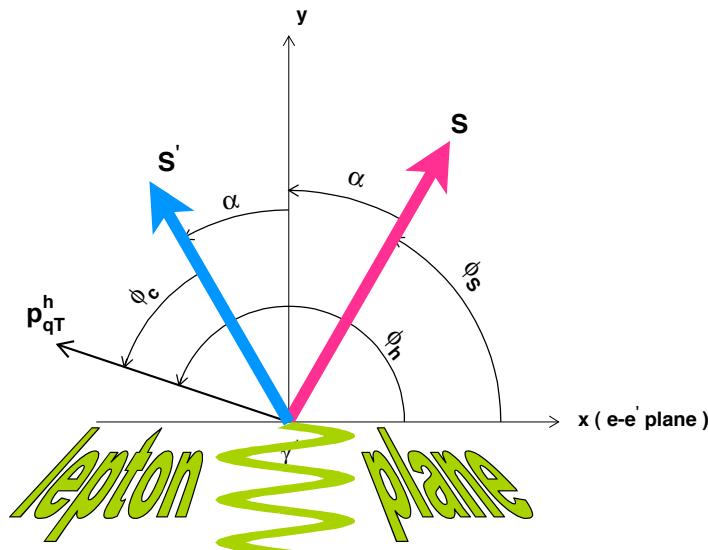


SIDIS xsec with *transverse target* polarization has **two** similar terms:

$$\sin(\phi_h^l + \phi_S^l) \Rightarrow h_1 = \text{Diagram} - \text{Diagram} \otimes H_1^\perp = \text{Diagram} - \text{Diagram}$$

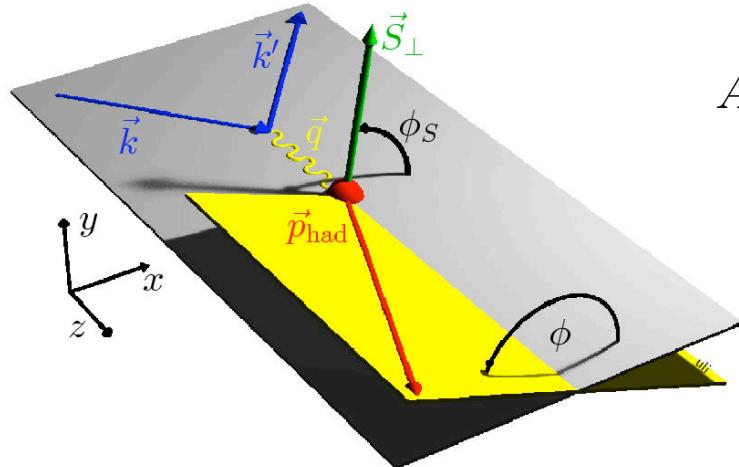
$$\sin(\phi_h^l - \phi_S^l) \Rightarrow f_{1T}^\perp = \text{Diagram} - \text{Diagram} \otimes D_1 = \text{Diagram}$$

separate *Sivers* and *Collins* mechanisms



- $(\phi_h^l - \phi_S^l)$ = angle of hadron relative to **initial quark spin**
- $(\phi_h^l + \phi_S^l) = \pi + (\phi_h^l - \phi_S^{l'})$ = hadron relative to **final quark spin**

Definition of Asymmetries and Moments



$$A_{\text{UT}}^h(\phi, \phi_S) = \frac{1}{|P_T|} \frac{N_h^\uparrow(\phi, \phi_S) - N_h^\downarrow(\phi, \phi_S)}{N_h^\uparrow(\phi, \phi_S) + N_h^\downarrow(\phi, \phi_S)}$$

$$= A_{\text{UT}}^{\text{Col}} \sin(\phi + \phi_S) + A_{\text{UT}}^{\text{Siv}} \sin(\phi - \phi_S)$$

→ fit amplitudes **simultaneously**

(prevents mixing of effects by acceptance)

Weighted moments

$$A_{\text{UT}}^{\text{Collins,wt}} = \frac{2 \langle \frac{Q_T}{M_\pi} \sin(\phi + \phi_S) \rangle_{\text{UT}}}{\langle 1 \rangle_{\text{UU}}} = |S_T| \frac{\sum_q e_q^2 \mathbf{h}_1^q \mathbf{H}_1^{\perp(1), q \rightarrow h}}{\sum_q e_q^2 f_1^q D_1^{q \rightarrow h}} \frac{1-y}{1-y+y^2/2}$$

$$A_{\text{UT}}^{\text{Sivers,wt}} = \frac{2 \langle \frac{Q_T}{M_\pi} \sin(\phi - \phi_S) \rangle_{\text{UT}}}{\langle 1 \rangle_{\text{UU}}} = |S_T| \frac{\sum_q e_q^2 \mathbf{f}_{1T}^{\perp,q} \mathbf{D}_1^{q \rightarrow h}}{\sum_q e_q^2 f_1^q D_1^{q \rightarrow h}}$$

Unweighted moments

$$A_{\text{UT}}^{\text{Collins}} = \frac{2 \langle \sin(\phi + \phi_S) \rangle_{\text{UT}}}{\langle 1 \rangle_{\text{UU}}} \sim A_{\text{UT}}^{\text{Collins,wt}} \cdot \frac{M_\pi z}{2 \langle P_{\pi \perp} \rangle} \quad (\text{in Gaussian ansatz})$$

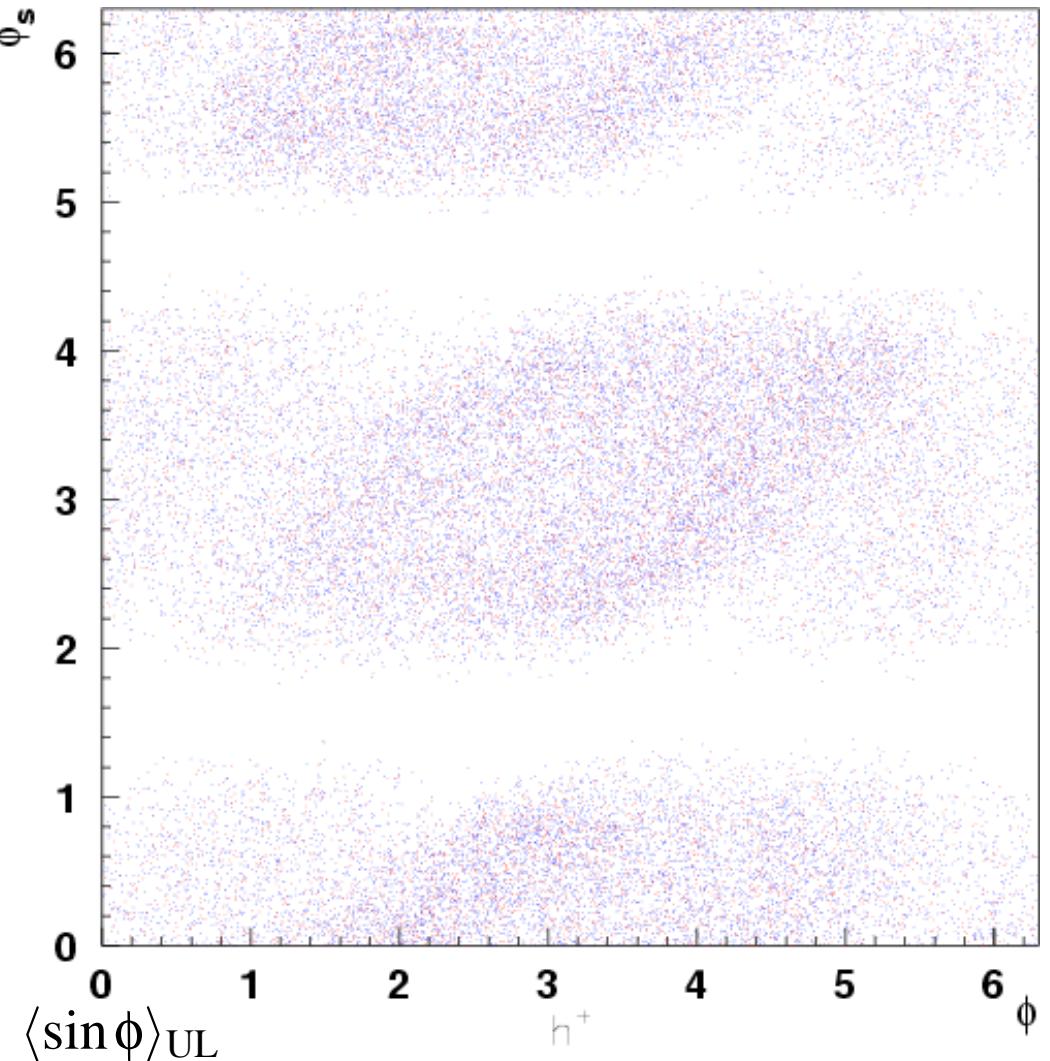
$$A_{\text{UT}}^{\text{Sivers}} = \frac{2 \langle \sin(\phi - \phi_S) \rangle_{\text{UT}}}{\langle 1 \rangle_{\text{UU}}} \sim A_{\text{UT}}^{\text{Sivers,wt}} \cdot \frac{M z}{2 \langle P_{\pi \perp} \rangle}$$

Acceptance coverage in Φ and Φ_S

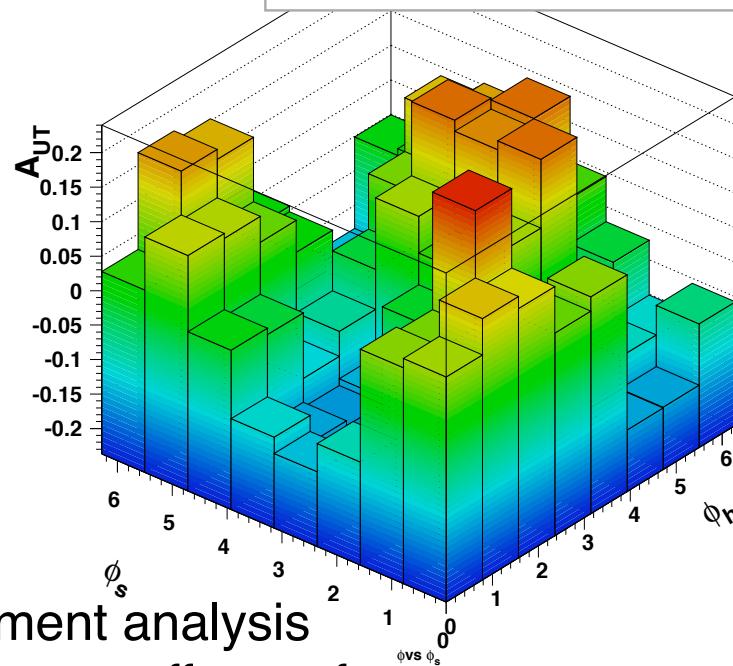
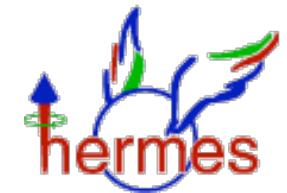


- **Good acceptance** in Φ and Φ_S , though not perfect
- Fit amplitudes $\langle \sin(\phi + \phi_S) \rangle$ and $\langle \sin(\phi - \phi_S) \rangle$ **simultaneously**

prevents mixing between
the two effects via the
acceptance



MC Test: Reconstruction of Moments

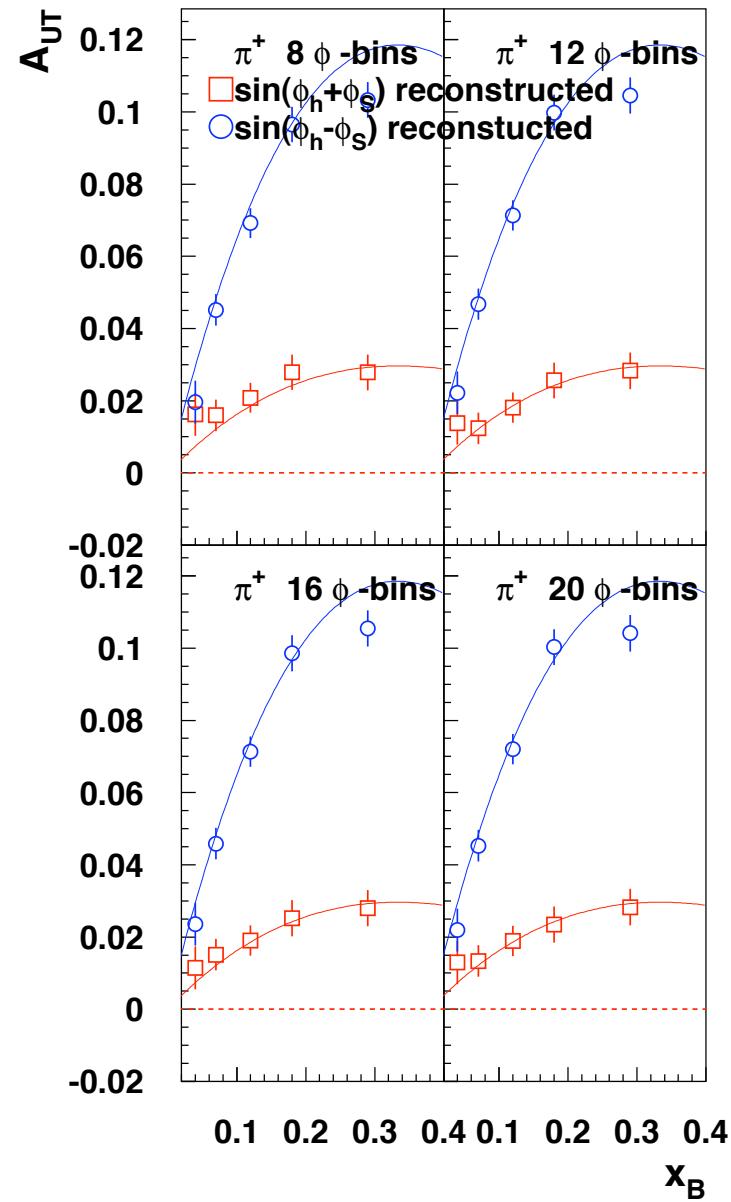


Moment analysis
robust to effects of

- acceptance & detector smearing
- QED radiation
- target holding field

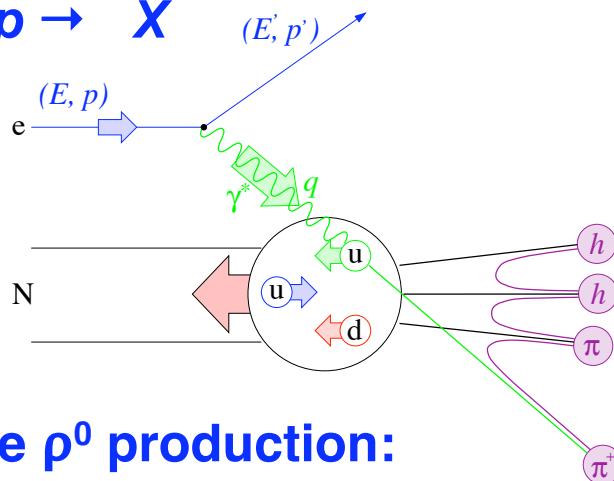
... and **many** more systematic studies
performed by **superb analysis crew**:

**Uli Elschenbroich, Ralf Seidl,
Markus Diefenthaler, Gunar Schnell**

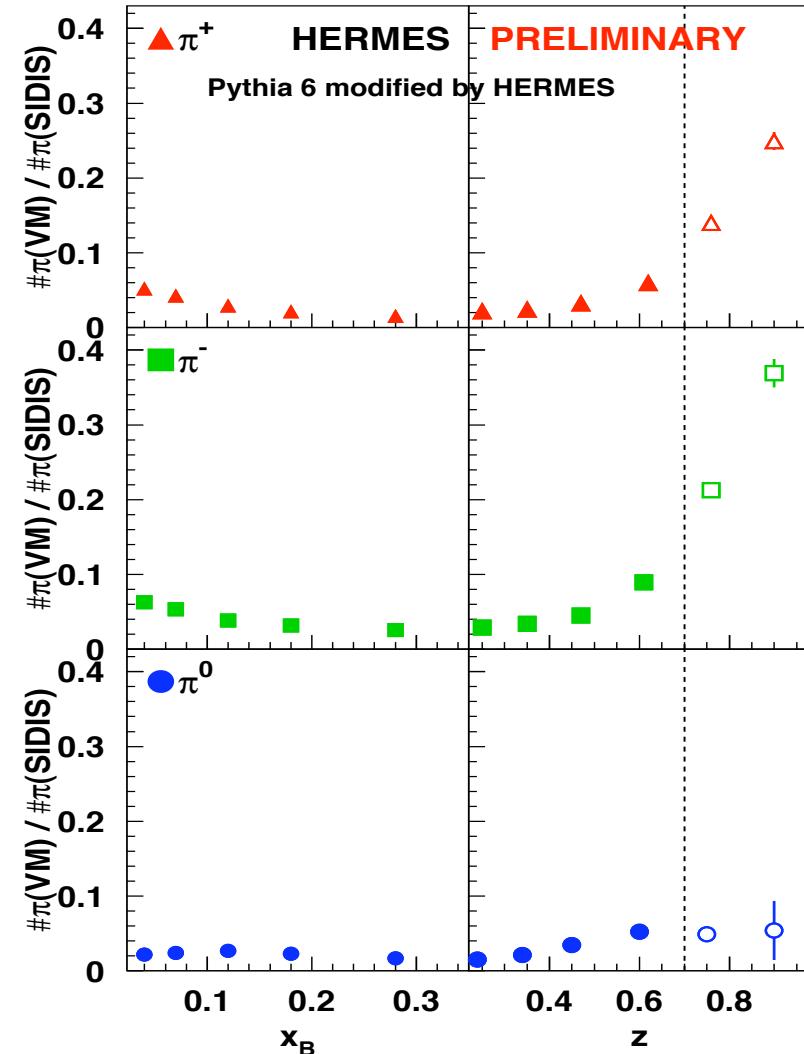
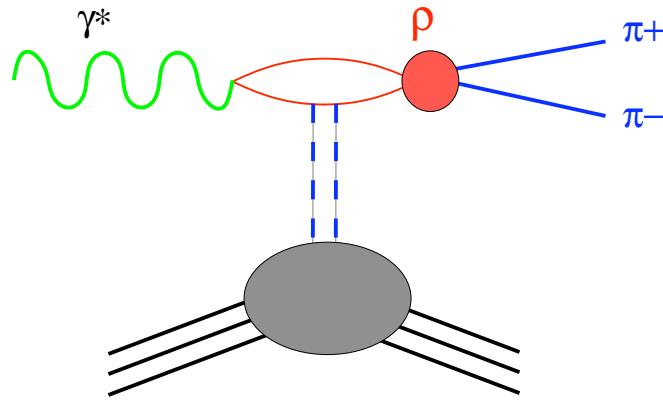


Interpretive Uncertainty from Diffractive VM Contribution

Desired process:
SIDIS $ep \rightarrow X$



Diffractive ρ^0 production:
different physics ... ?

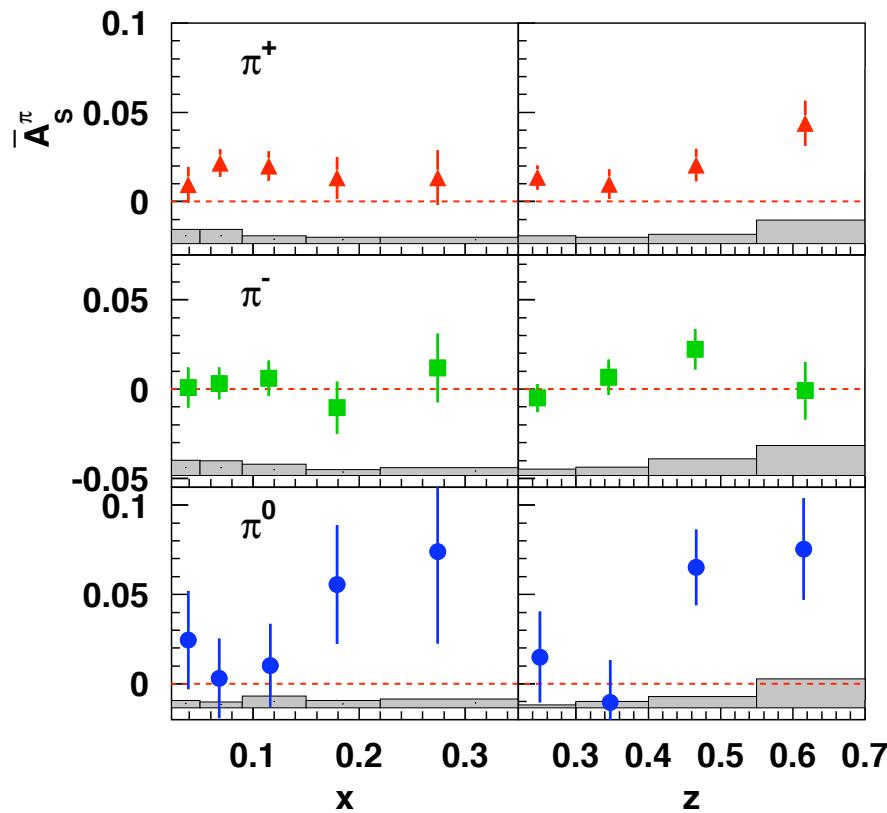


Conservative approach: for now, calculate “systematic error”
for full range of possible diffractive ρ asymmetries

Published Results from 2002/03: H[↑] Target

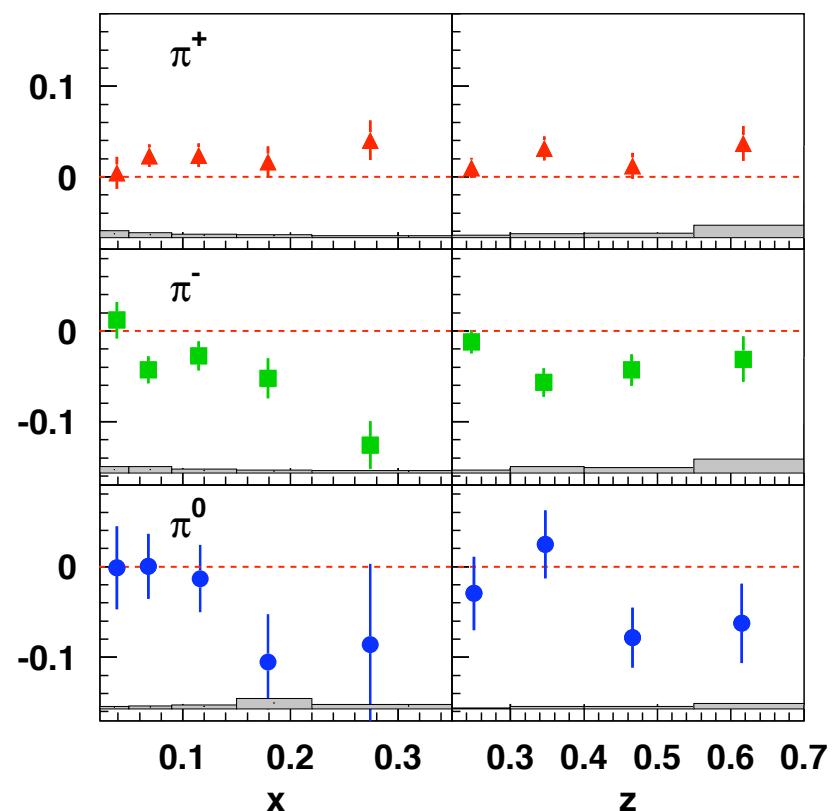


Sivers Moments for $\pi^+ \pi^- \pi^0$



Sivers $\langle A^{\pi^+} \rangle = 0.034 \pm 0.008$
 $\Rightarrow 3\sigma$ away from zero

Collins Moments for $\pi^+ \pi^- \pi^0$

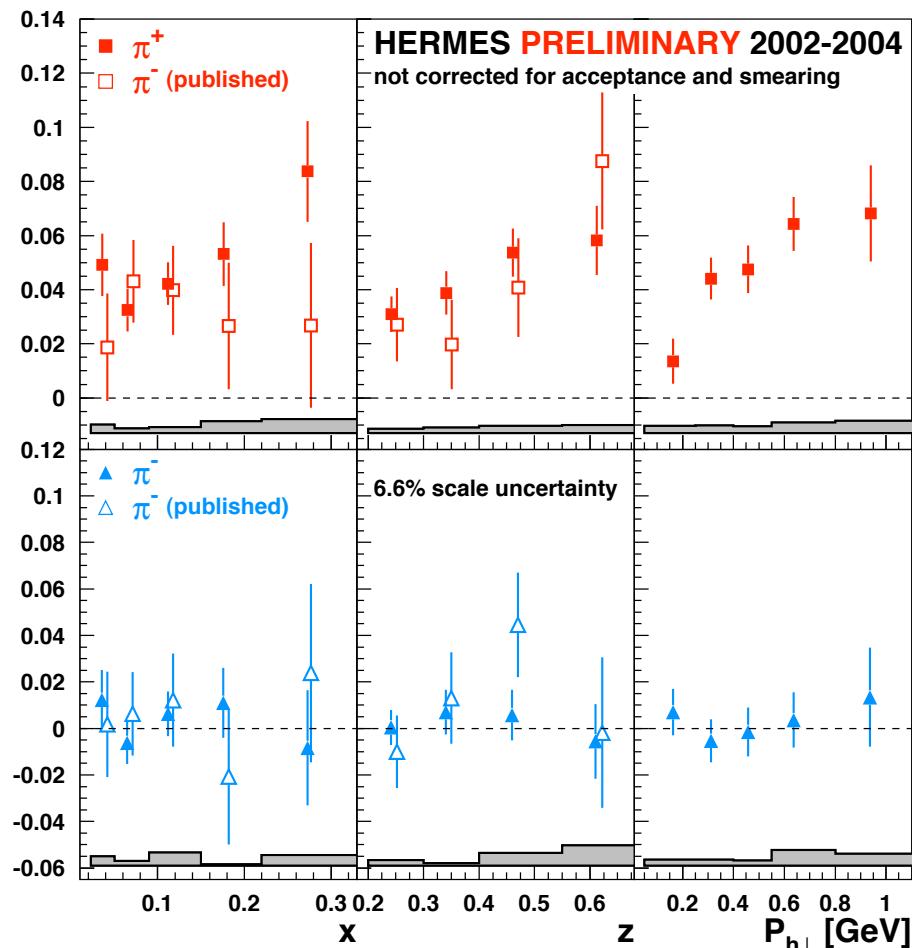


Collins asym large for $\bar{}$, small for $+$

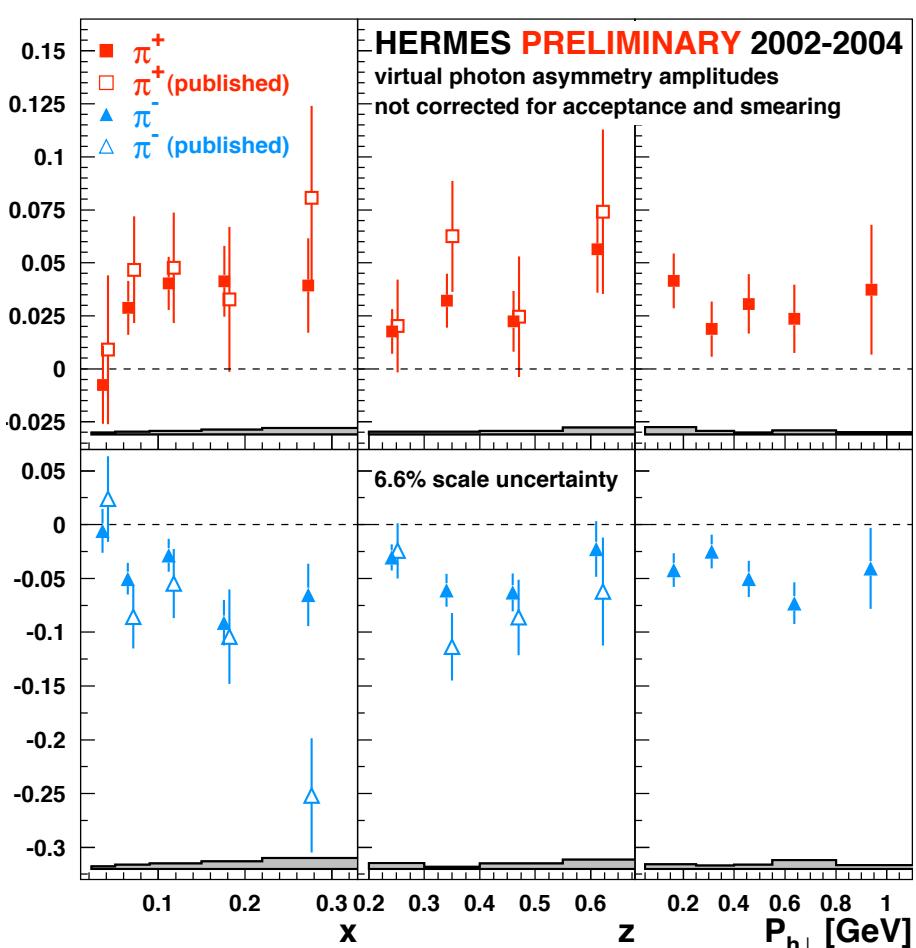
New Results from 2002–2004: H^\uparrow Target



Sivers Moments for $\pi^+ \pi^-$



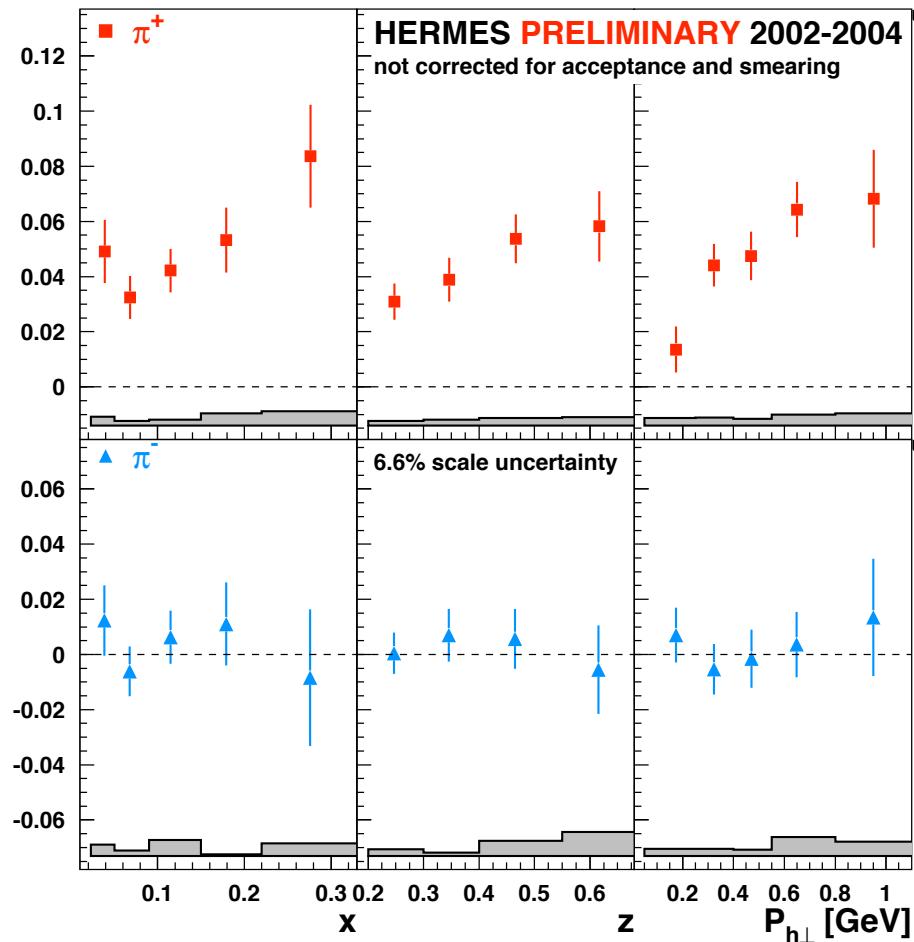
Collins Moments for $\pi^+ \pi^-$



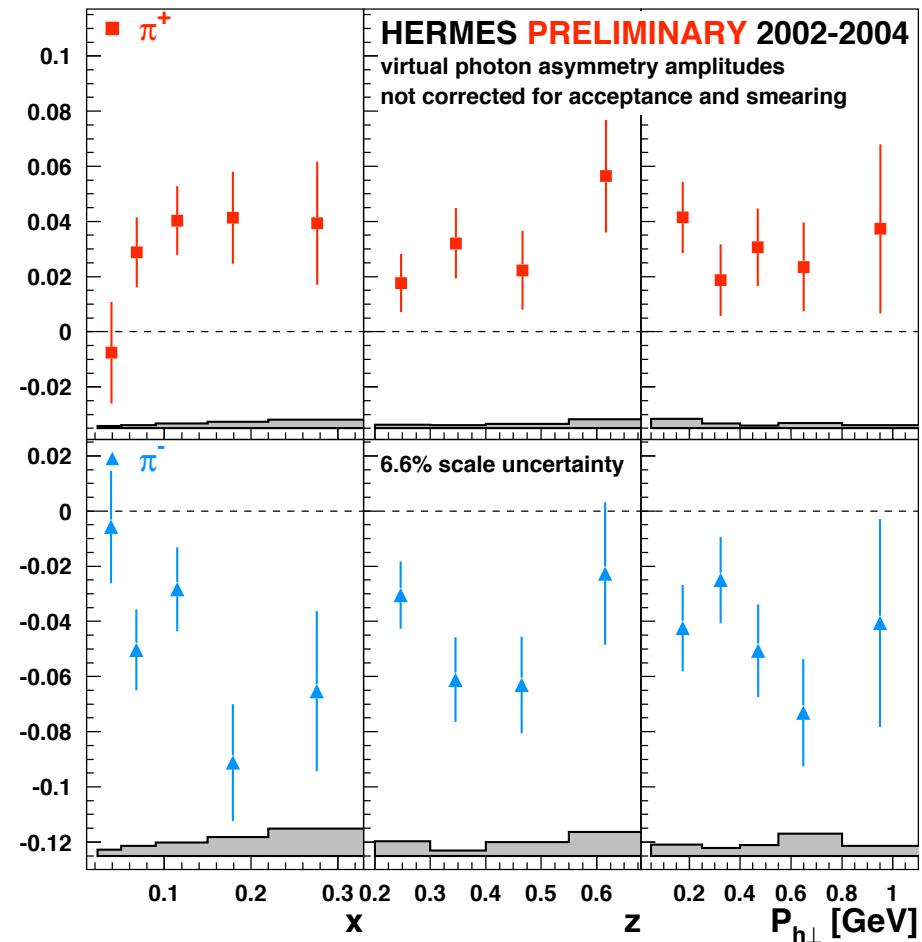
New Results from 2002–2004: H \uparrow Target



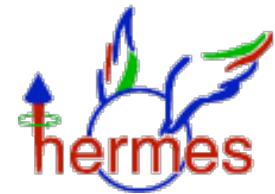
Sivers Moments for $\pi^+ \pi^-$



Collins Moments for $\pi^+ \pi^-$



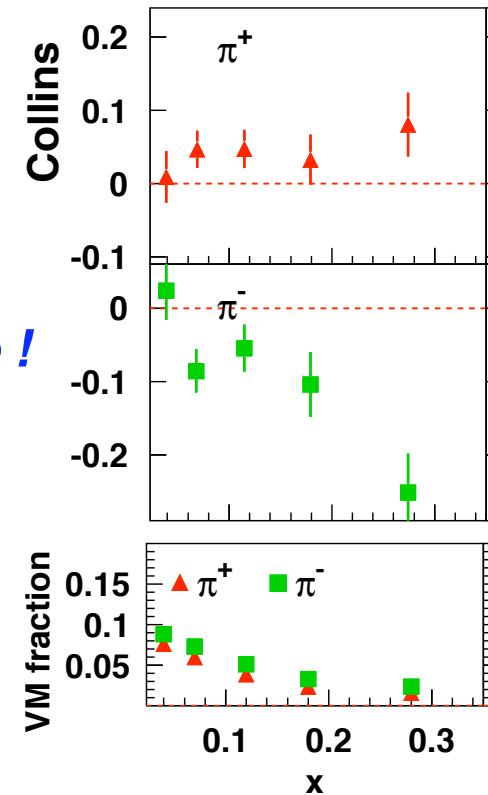
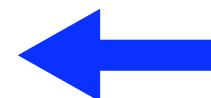
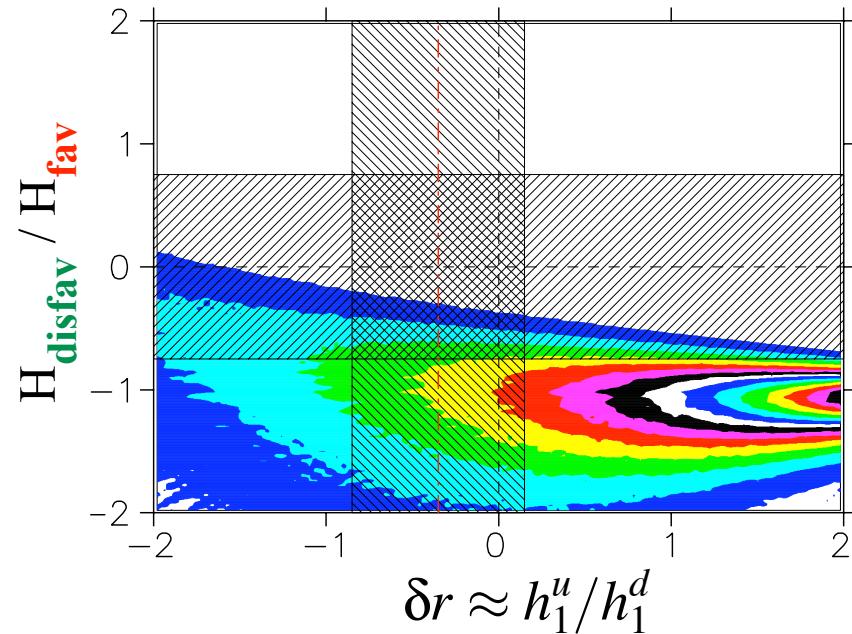
Why are the Collins π^- asymmetries so large?



DIS on proton target always dominated by ***u-quark scattering***

- $A_{\text{Col}}^{\pi^+} \sim h_1^u H_{1,\text{favored}}^\perp$... expect: **positive**
- $A_{\text{Col}}^{\pi^-} \sim h_1^u H_{1,\text{disfavored}}^\perp$... expect: **~ zero**

Data indicate ***disfavored*** CollinsFF is ***large & negative !***



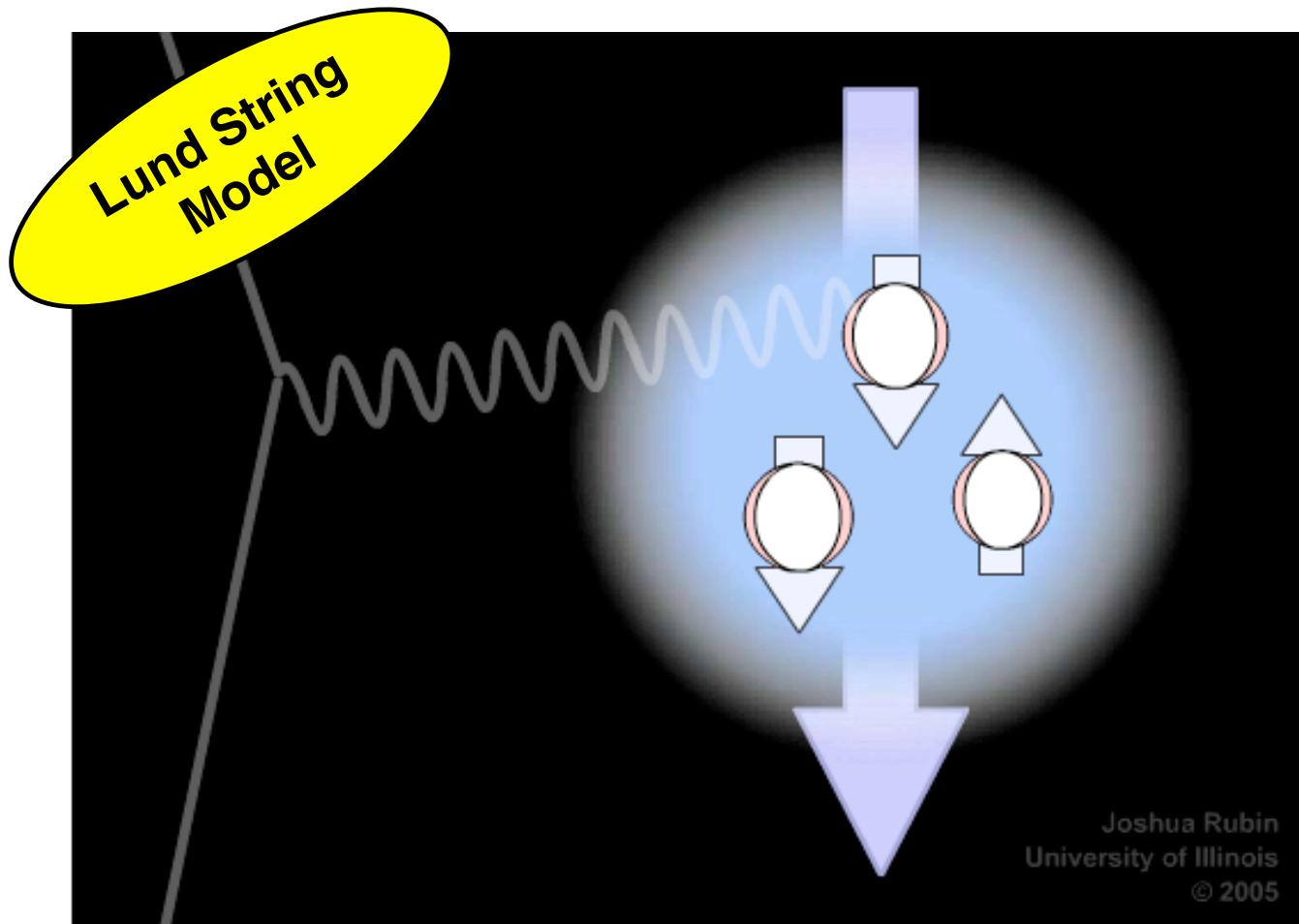
Map out solution space ...
find $H_{\text{disfav}} \approx -H_{\text{fav}}$

Understanding the Collins Effect



The Collins function exists! → **spin-orbit** correlations in π formation

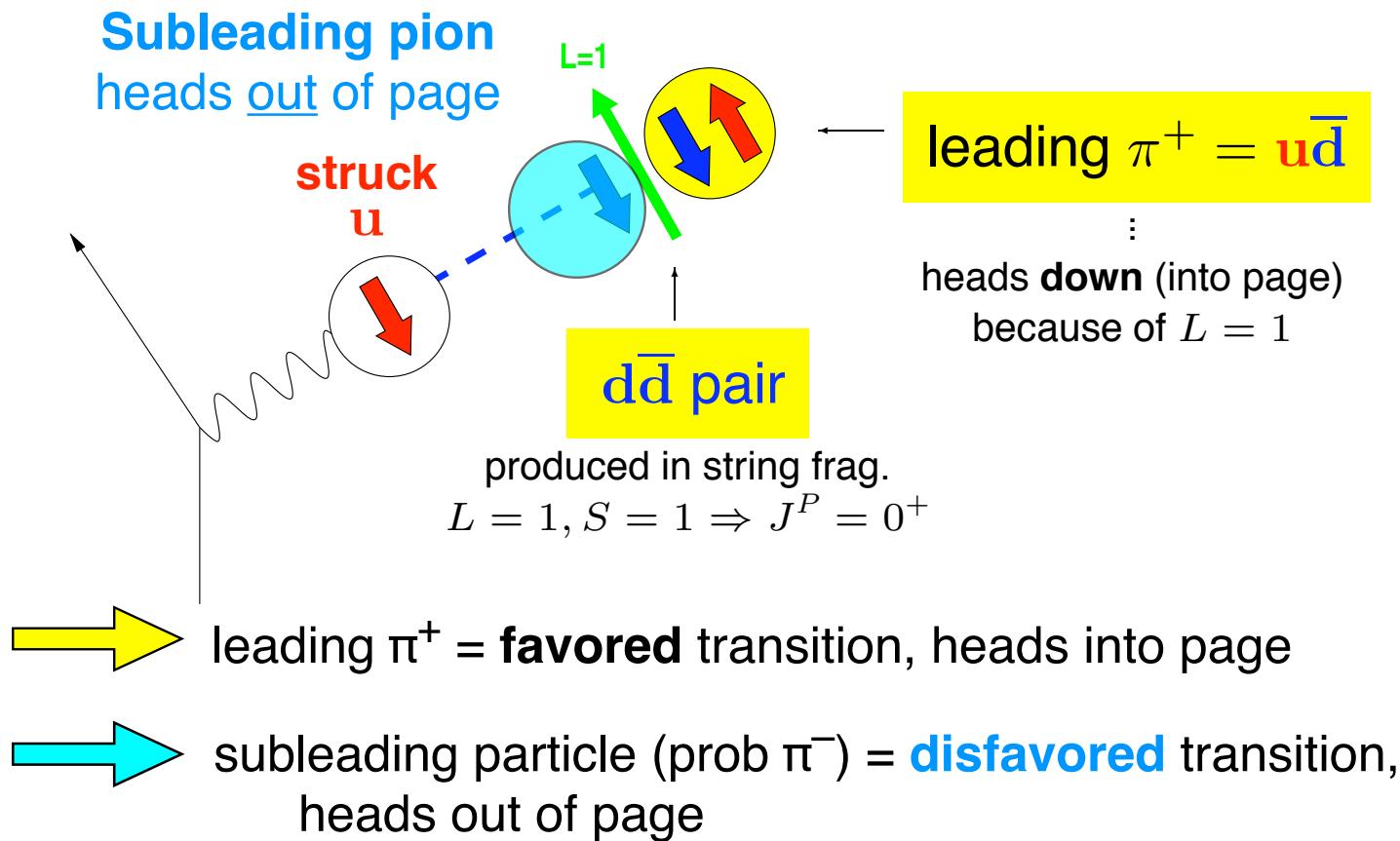
Is the Artru mechanism responsible?



Interpretation of Collins Results



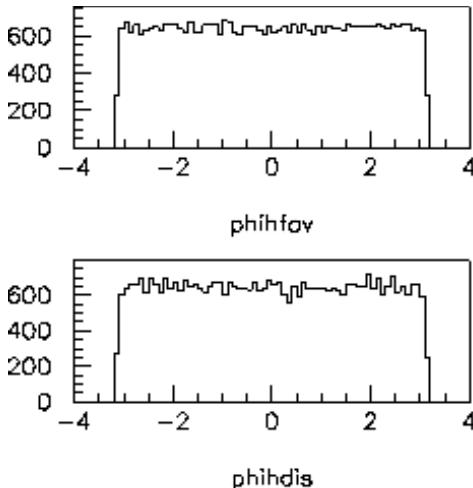
Artru model, based on phenomenological **Lund string-fragmentation model** and 3P_0 hypothesis for qqbar-pair formation



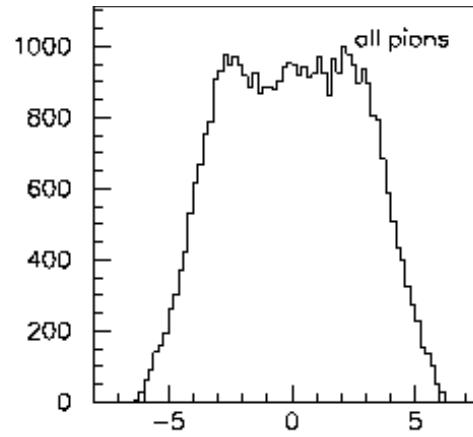
Perhaps $H_{\text{dis}} \approx -H_{\text{fav}}$ is not only reasonable, but likely ?

Check unpolarized Lund Monte Carlo for any Φ correlation between favored and disfavored pions within an event ...

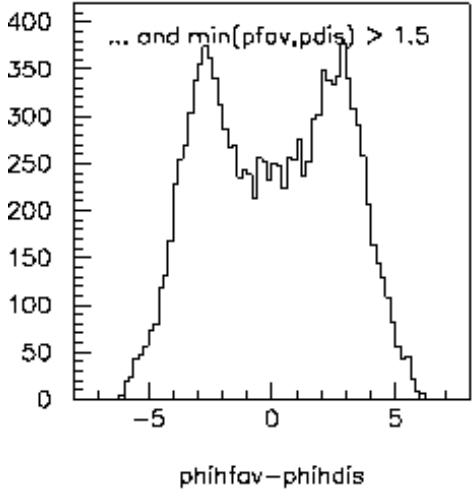
no cuts



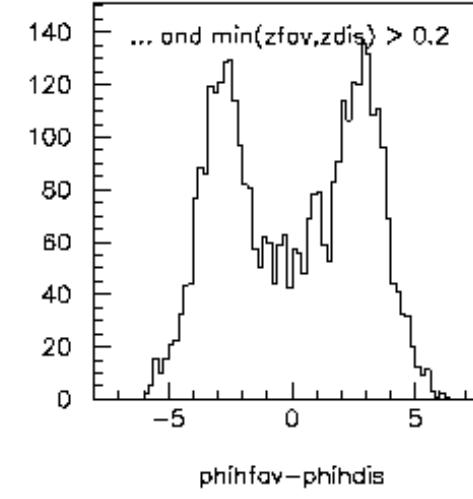
no cuts



both pions with
p > 1.5 GeV



... and both
with z > 0.2



Clear ***anti-correlation*** between fav / disfav pions in forward region ($z > 0.2$), due to ***transverse-momentum conservation*** and ***ordering of string breaks*** in Lund model

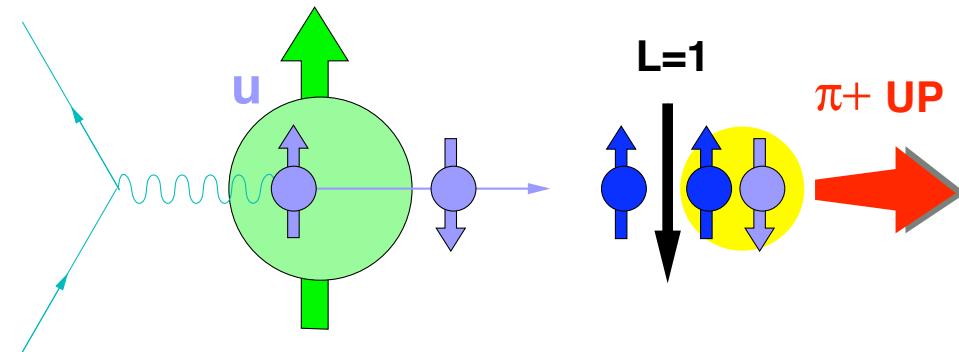
Sign of the Collins Effect: does the Artru Model get it right?

Observation: $\langle \sin(\phi_h^l + \phi_S^l) \rangle_{\text{UT}}^{\pi^+} > 0$ (and opposite for pi-)

Assuming that $h_1^u > 0$ **and** $h_1^d < 0 \dots$

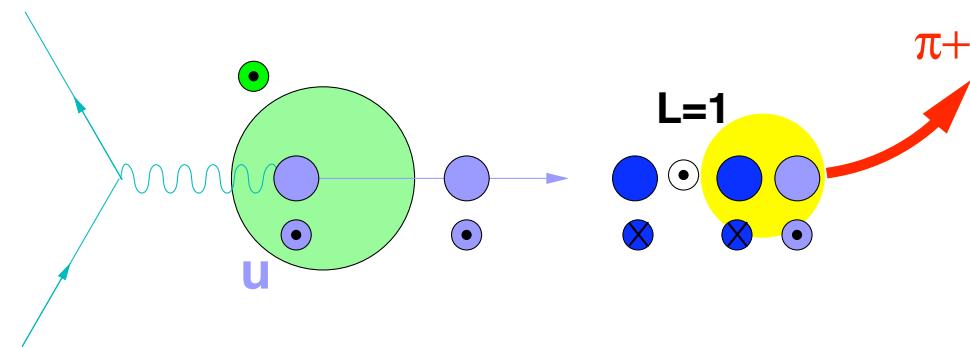
We observe: for $\phi_S^l = 0$

$\phi_h^l = \pi/2$ is preferred ...



We observe: for $\phi_S^l = \pi/2$

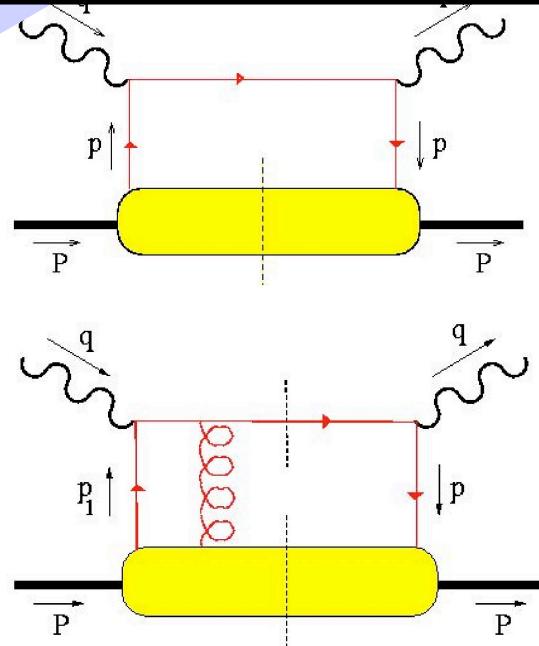
$\phi_h^l = 0$ is preferred ...



It actually works !!? Wow ...



Heisenberg Picture

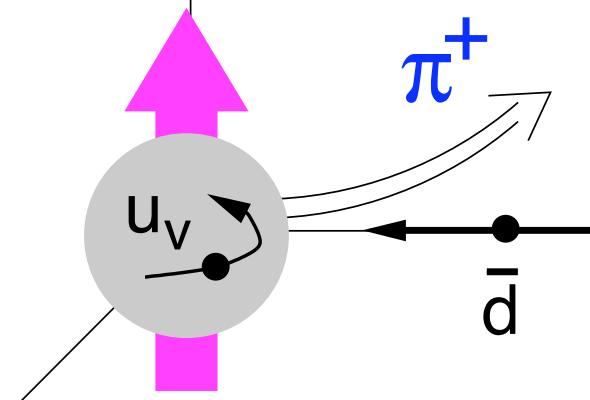


Requires:

- rescattering via gauge link
- interference effect involving L=0 and L=1 states

Schroedinger Picture

Model of Meng, Chou, Yang



Trento 2004 featured a splendid **theoretical synthesis** of field-theoretic analysis (*rigour*) and phenomenological thinking (*intuition*)

So what is the sign of L ?

My mangled-version of a lunch-time insight from M. Burkhardt

- Constituent quark model (CQM) says $\Delta u = +4/3$, $\Delta d = -1/3$
- CQM does a great job of explaining the proton anomalous magnetic moment, via $\mu_p \sim \sum_q e_q / m_q \Delta q$
- ... but we know that the quarks are not as highly polarized as in the CQM
- Missing piece must come from $\sum_q e_q L_q$ and must be positive
- Therefore L_u must be positive!

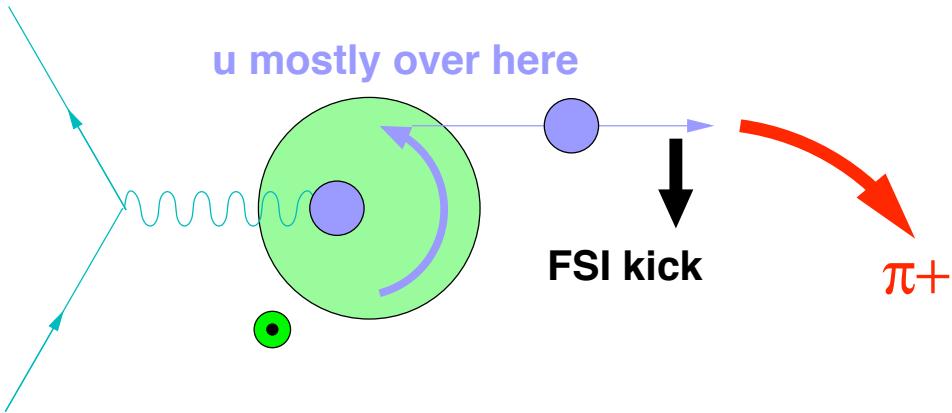


***Numerous model calculations give $L_u > 0$ and $L_d < 0$
i.e. quark angular momentum shared between spin and L***

Dynamical Models for Sivers Mechanism

Trento Work
Laszlo Sümmerer
M. Burkardt: Chromodynamic lensing

Electromagnetic coupling $\sim (J_0 + J_3)$ **stronger for oncoming quarks**



We observe $\langle \sin(\phi_h^l - \phi_S^l) \rangle_{\text{UT}}^{\pi^+} > 0$

(and opposite for π^-)

\therefore for $\phi_S^l = \pi/2$, $\phi_h^l = \pi$ preferred...

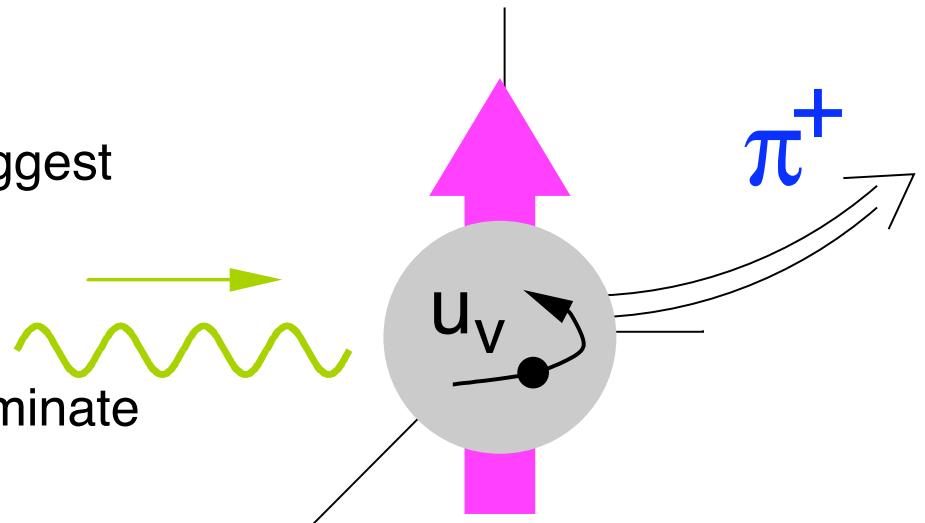
Model agrees!

D. Sivers: Jet Shadowing

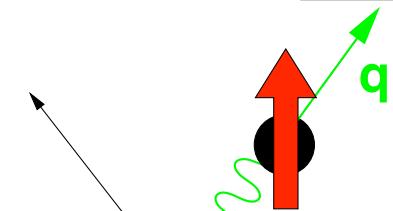
Parton energy loss considerations suggest
quenching of jets from
“near” surface of target

→ quarks from “far” surface should dominate

Opposite sign to data ...



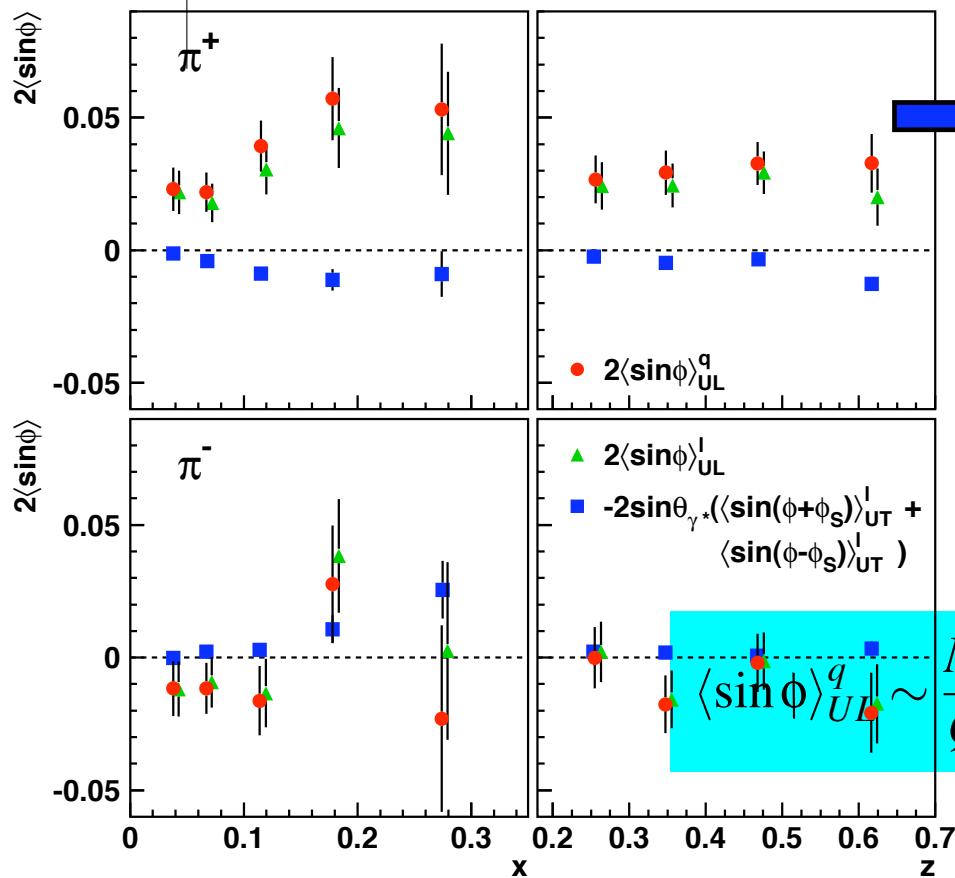
Revisiting the Longitudinal Target SSA's



Experiment: “longitudinal target” polarized // **lepton beam /**
 Theory: “longitudinal target” polarized // **virtual photon q**

With both targets measured, can now extract pure **UL** moments

$$\langle \sin \phi \rangle_{UL}^q = \langle \sin \phi \rangle_{UL}^l + \sin \theta_\gamma * [\langle \sin(\phi + \phi_S) \rangle_{UT}^l + \langle \sin(\phi - \phi_S) \rangle_{UT}^l]$$



Correction is small: as anticipated earlier, A_{UL} **is** almost-entirely longitudinal (i.e. **twist-3**) in origin

Recent, more complete theoretical analysis of **sub-leading** $A_{UL}(\Phi)$ includes contribution from **twist-3 Sivers function f_{L^\perp}**

$$\frac{M}{Q} \frac{I[g_{1L} G^\perp \oplus h_L H_1^\perp \oplus h_{1L}^\perp \tilde{H} \oplus f_L^\perp D_1]}{f_1 D_1}$$

Theoretical revisit needed ...

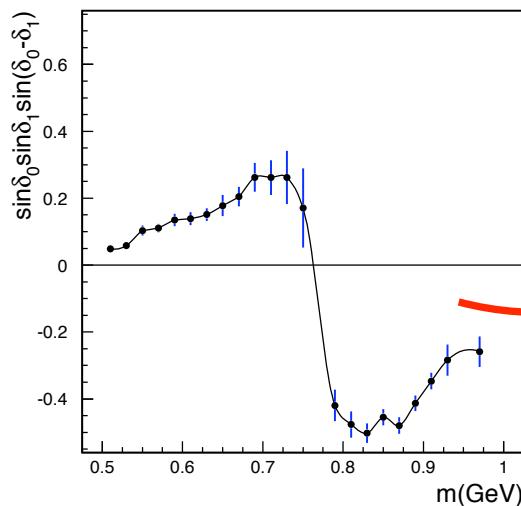
$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin \theta h_1 H_1^{\triangleleft}$$

Expansion of H_1^{\triangleleft} in Legendre moments:

$$H_1^{\triangleleft}(z, \cos \theta, M_{\pi\pi}^2) = H_1^{\triangleleft, sp}(z, M_{\pi\pi}^2) + \cos \theta H_1^{\triangleleft, pp}(z, M_{\pi\pi}^2)$$

about $H_1^{\triangleleft, sp}$:

describe interference between 2 pion pairs
coming from different production channels.



Jaffe et al. [[hep-ph/9709322](#)]:

$$\begin{aligned} H_1^{\triangleleft, sp}(z, M_{\pi\pi}^2) &= \frac{\sin \delta_0 \sin \delta_1 \sin(\delta_0 - \delta_1)}{\delta_0 (\delta_1)} H_1^{\triangleleft, sp'}(z) \\ &= \mathcal{P}(M_{\pi\pi}^2) H_1^{\triangleleft, sp'}(z) \end{aligned}$$

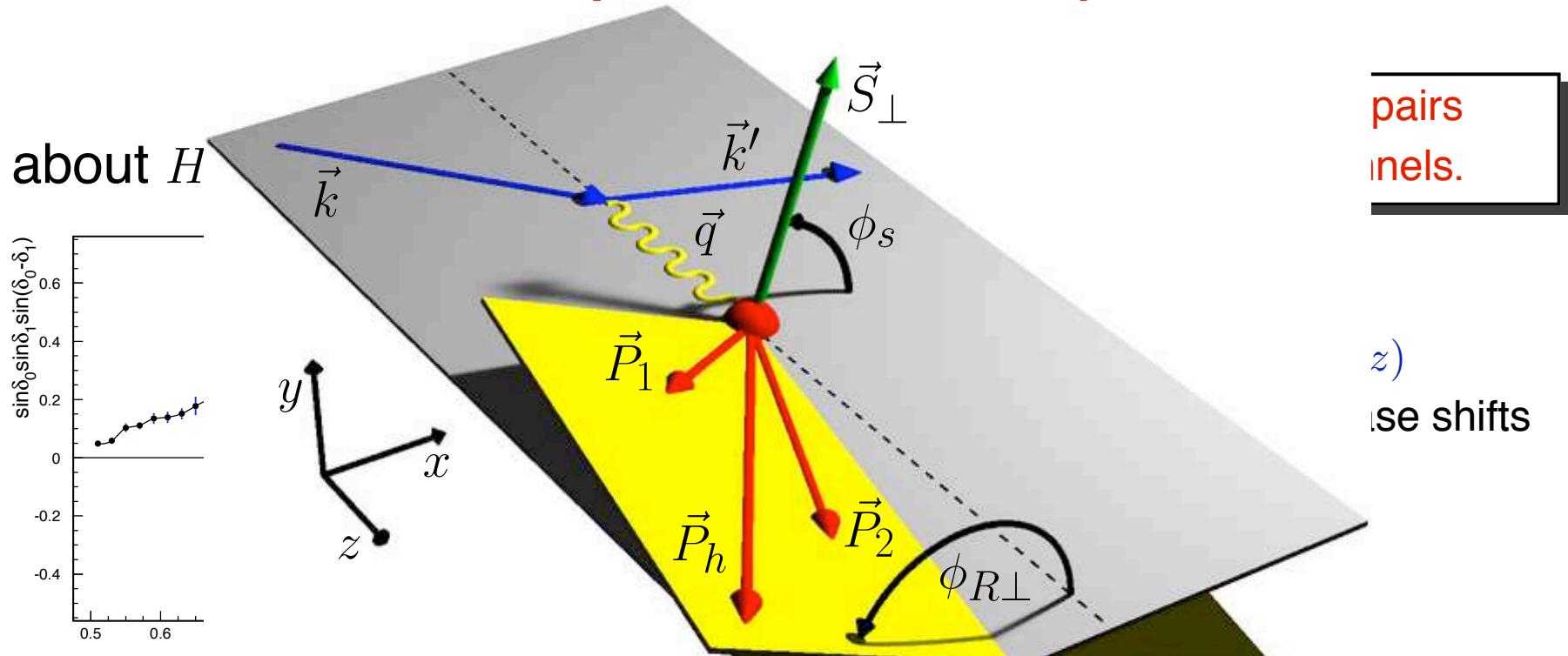
$\implies A_{UL}^{\sin \phi_{R\perp}}$ might depend strongly on $M_{\pi\pi}$

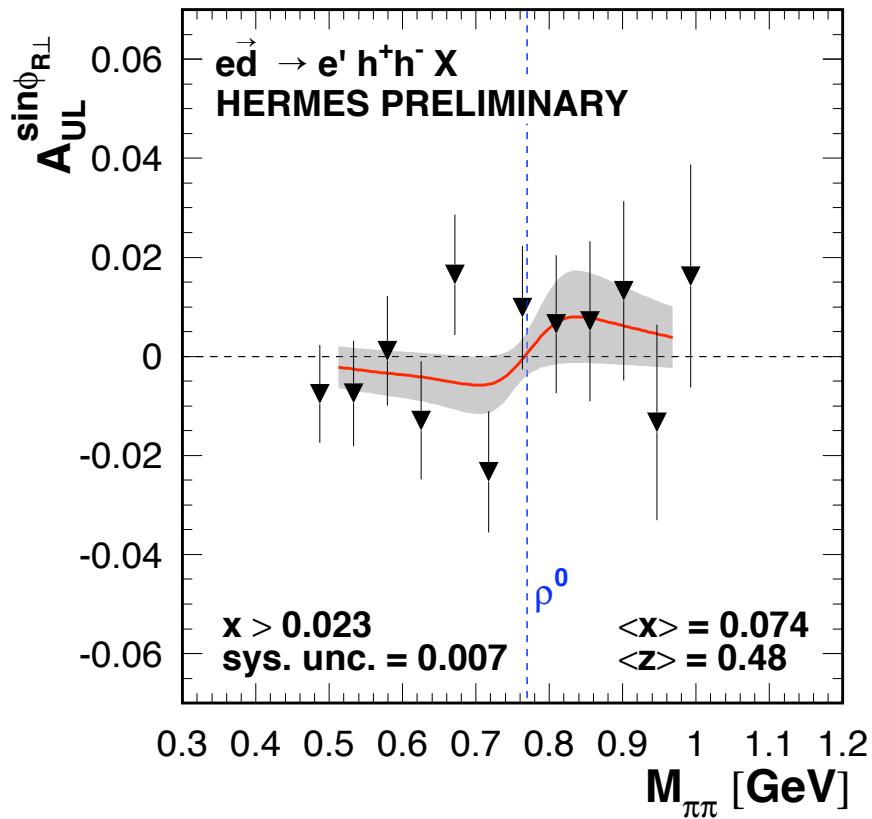
Slide from Paul van der Nat, DIS 2005

$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin \theta h_1 H_1^\triangleleft$$

Expansion of H_1^\triangleleft in Legendre moments:

$$H_1^\triangleleft(z, \cos \theta, M_{\pi\pi}^2) = H_1^{\triangleleft, sp}(z, M_{\pi\pi}^2) + \cos \theta H_1^{\triangleleft, pp}(z, M_{\pi\pi}^2)$$



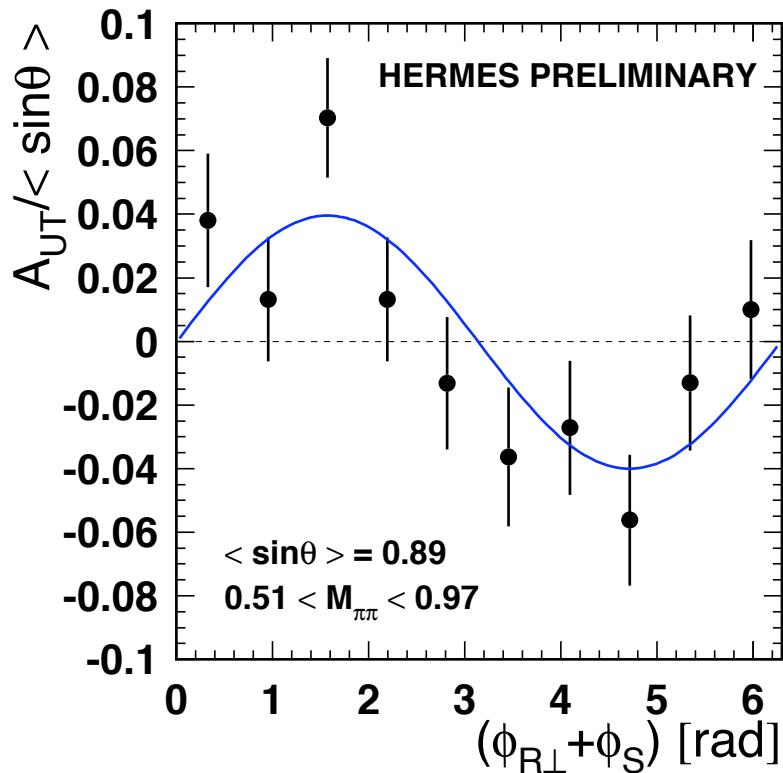


$$c_1 = 0.040 \pm 0.036$$

$$c_2 = -0.001 \pm 0.004$$

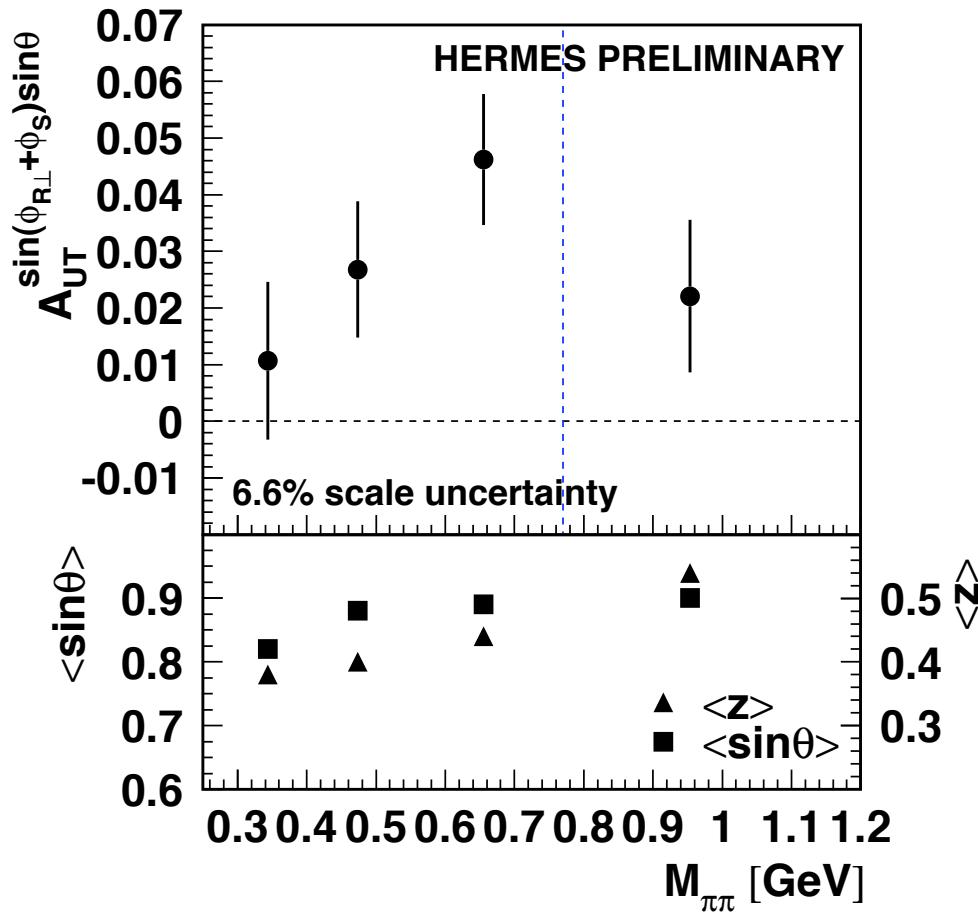
- hint of a sign change at the ρ^0 mass

$$g(M_{\pi\pi}^2) \simeq c_1 \mathcal{P}(M_{\pi\pi}^2) + c_2$$



significant $\sin(\phi_{R\perp} + \phi_S)$
behavior!

$$A_{UT}^{\sin(\phi_{R\perp} + \phi_S) \sin \theta} = 0.040 \pm 0.009 \text{ (stat)} \pm 0.003 \text{ (syst)}$$



- positive asymmetry moment for all invariant mass bins
- result rules out predicted sign change at the ρ^0 mass (Jaffe et al.)

Where the following binning was used: 0.25 - 0.40 - 0.55 - 0.77 - 2.0

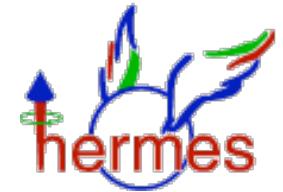
Slide from Paul van der Nat, DIS 2005

Conclusions and Outlook



- **Sivers** effect is **non-zero** in DIS!
- Large, negative **Collins** asymmetry measured for π^- , smaller and positive for π^+
- Apparent implication: **disfavored** Collins fragmentation function of **opposite sign** and similar magnitude to **favored** function
- New data from 03–04 **confirms** these results with x4 statistics
- In progress: analysis of **Sivers function** for individual quark flavors (via **purity analysis**)
- Need **global analysis** of new data + older data from longitudinal target & hadronic reactions → in progress (Anselmino & co.)
... and especially new **Belle data** on Collins function

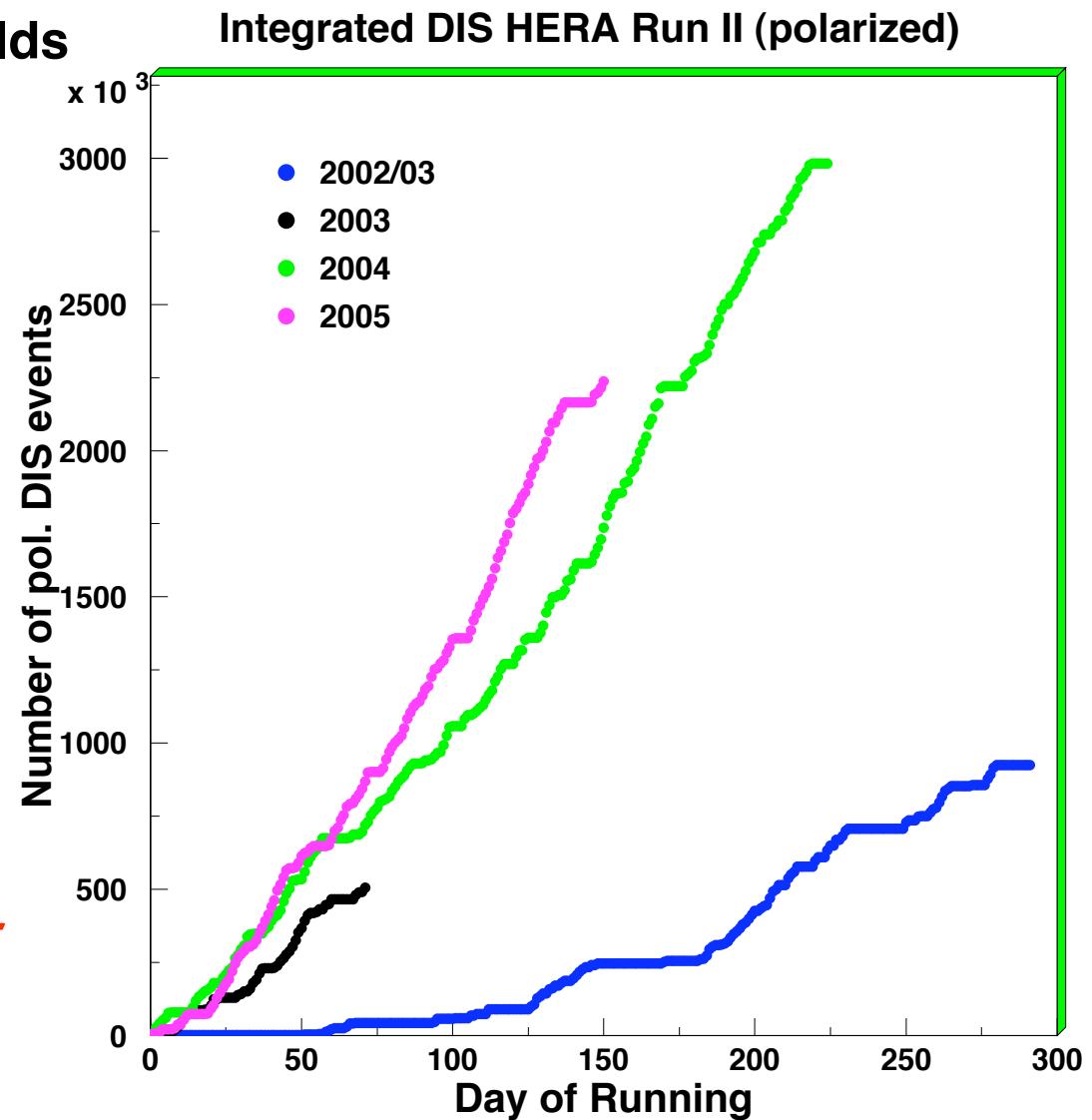
HERMES Run 2: Tale of the Tape



Transversely polarized DIS yields

(before data quality cuts):

- 2002/03 (published):
0.9 M DIS
- Nov - Dec 2003:
0.5 M DIS
- Jan - Aug 2004:
3 M DIS :-)
- Dec 2004 - May 2005:
2.3 M DIS & counting ...
- *run extended to November
⇒ cross your fingers !*



Backup Slides

Interpretation: Minimal Assumptions

- $A_{\text{UT}}^{\text{Collins}}$ is ***leading twist***
- Collins FF obeys ***favored / disfav*** symmetry:

$$H_{\text{fav}} \equiv H_{1\perp}^{u \rightarrow \pi^+} = H_{1\perp}^{d \rightarrow \pi^-} = H_{1\perp}^{\bar{u} \rightarrow \pi^-} = H_{1\perp}^{\bar{d} \rightarrow \pi^+}$$

$$H_{\text{dis}} \equiv H_{1\perp}^{u \rightarrow \pi^-} = H_{1\perp}^{d \rightarrow \pi^+} = H_{1\perp}^{\bar{u} \rightarrow \pi^+} = H_{1\perp}^{\bar{d} \rightarrow \pi^-}$$

$$\Rightarrow A^{\pi^+} = k \frac{(4\delta u + \delta \bar{d})H_{\text{fav}} + (\delta d + 4\delta \bar{u})H_{\text{dis}}}{(4u + \bar{d})D_{\text{fav}} + (d + 4\bar{u})D_{\text{dis}}}$$

Some definitions

$$r \equiv \frac{d + 4\bar{u}}{u + \bar{d}/4} \quad \eta \equiv \frac{D_{\text{dis}}}{D_{\text{fav}}}$$

$$\delta r \equiv \frac{\delta d + 4\delta \bar{u}}{\delta u + \delta \bar{d}/4} \quad \eta_H \equiv \frac{H_{\text{dis}}}{H_{\text{fav}}}$$

Consider Asymmetry Ratios

$$\alpha^- \equiv \frac{A^{\pi^-}}{A^{\pi^+}} = \left(\frac{4\eta_H + \delta r}{4\eta + r} \right) \left(\frac{4 + r\eta}{4 + \delta r\eta_H} \right), \quad \alpha^0 \equiv \frac{A^{\pi^0}}{A^{\pi^+}} = \frac{(4 + \delta r)(1 + \eta_H)}{(4 + r)(1 + \eta)} \left(\frac{4 + r\eta}{4 + \delta r\eta_H} \right)$$

⇒ Leads to Constraint Equⁿ involving only unpolarized quantities

$$\alpha^- C = \alpha^0(1 + C) - 1 \quad \text{where} \quad C \equiv \frac{4\eta + r}{4 + \eta r}$$

⇒ Solution Space in η_H vs δr can be determined:

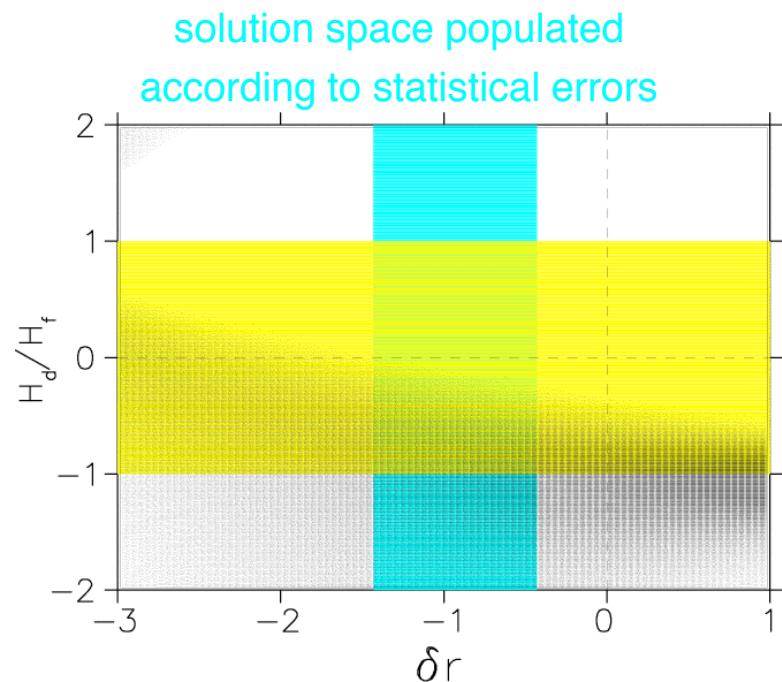
$$\eta_H = \frac{\delta r - 4(\alpha^- C)}{(\alpha^- C)\delta r - 4} \quad \text{and} \quad \eta_H = \frac{\delta r - 4(\alpha^0(1 + C) - 1)}{(\alpha^0(1 + C) - 1)\delta r - 4}$$

Interpretation of Collins Results

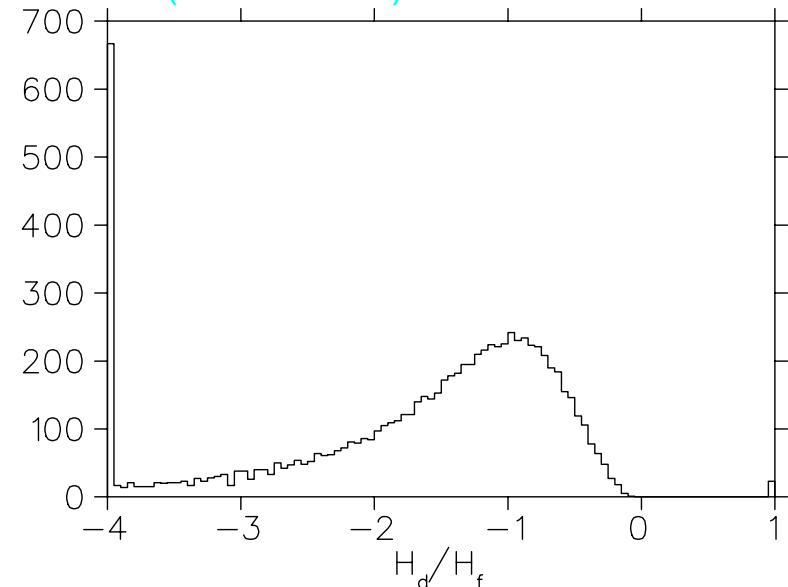


① **Constraint equation:** well satisfied by both weighted and unweighted asymmetries (within 1σ statistical) → no problem with internal consistency

② **Solution space** for $\delta r \approx \delta d/\delta u$ vs $\eta_H = H_{\text{dis}}/H_{\text{fav}}$



η_H solutions at χ QSM value
(Wakamatsu) $\delta r = -0.93$



Neglecting possible diffractive contamination, there seems to be a pronounced indication that $H_{\text{fav}} \approx -H_{\text{dis}}$